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AERODYNAMIC CHARACTERISTICS

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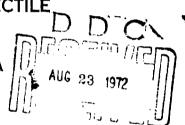
OF THE

SPIN-STABILIZED. 4.2 INCH M329A1E1

MORTAR PROJECTILE

R. KLINE W. GAZDAYKA

JUNE 1972



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Technical Report 4300

AERODYNAMIC CHARACTERISTICS AND SUBSONIC FLIGHT PERFORMANCE OF THE SPIN-STABILIZED, 4.2 INCH M329A1E1 MORTAR PROJECTILE

by

R. Kline W. Gazdayka

JUNE 1972

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NOMENCLATURE

α	Angle of attack, degrees
8	Angle of sideslip, degrees
$^{\mathrm{C}}_{\mathrm{D}_{_{0}}}$	Axial force coefficient, $F_X/\overline{Q}S$
$^{\mathrm{C}}{}_{\mathbf{1_{p}}}$	Roll damping moment coefficient, $L_p/\overline{Q} \operatorname{Sd}\left(\frac{\operatorname{pd}}{2\operatorname{V}}\right)$
C _m	Pitching moment coefficient, m/QSd
C _m	Pitching moment coefficient derivative, 1/rad
C _m ,	Flow lag moment coefficient, $m_{\dot{\alpha}}/\overline{Q} \operatorname{Sd}\left(\frac{\dot{\alpha}^{\dot{d}}}{2V}\right)$
C _{mq}	Damping moment coefficient, $m_q/\overline{Q} Sd\left(\frac{qd}{2V}\right)$
$^{\mathrm{C}}{}_{\mathrm{N}}$	Normal force coefficient, N/QS
$^{\mathrm{C}}{}_{\mathrm{N}_{_{_{lpha}}}}$	Normal force coefficient derivative, ${}^{\partial C}_{N}/{}^{\partial}\alpha$
C ₁₁ p	Magnus moment coefficient, $n_M/\overline{Q} \operatorname{Sd}\left(\frac{pd}{2V}\right)$
$^{ extbf{C}}_{ extbf{n}_{ extbf{p}lpha}}$	Magnus moment coefficient derivative, $\partial C_n / \partial_0$, $1/rad$
с _{пра}	Magnus force coefficient, $F_{Y}/\overline{Q} Sc\left(\frac{pd}{2V}\right)$
$^{\mathrm{C}}{}^{\mathrm{p}_{lpha}}$	Magnus force coefficient derivative, $\partial C_{\begin{subarray}{c} \gamma \end{subarray}}/\partial_{\alpha}$, 1/rad p
d, D	Diameter, ft
$\mathbf{F}_{\mathbf{X}}$	Axial force, 1b

$I_{\mathbf{x}}$	Axial moment of inertia, slugs - ft ²
ľ	Transverse moment of inertia, slugs - ft ²
κ_1	Magnitude of nutation arm, degrees
к2	Magnitude of precession arm, degrees
$^{L}_{p}$	Roll damping moment, ft-lb
λ_{1}	Quasi linear nutation arm damping factor, 1/sec
λ_2	Quasi linear precession arm damping factor, 1/sec
N	Normal force, 1b
ⁿ M	Magnus moment, ft-lb
$\mathbf{F}_{\mathbf{Y}}$	Magnus force 1b
M	Mach number
m_{q}	Damping moment, due to pitching velocity, ft-lb
m, å	Flow lag moment, ft-lb
m	Pitching moment, ft-lb
p	Roll rate, rad/sec
ହ	Dynamic pressure, lb/ft ²
q	Pitch rate, rad/sec
QE	Quadrant elevation, mils or degrees, as noted
,•	Air density, slugs/ft ³
s g	Gyroscopic stability factor
S	Reference area, ft ²

V Free stream or flight velocity, ft/sec θ Sun angle, degrees Nutation frequency, rad/sec ω_1 Precession frequency, rad/sec ω_2 XCG Center of gravity location, calibers from nose XCPCenter of pressure of normal force, calibers from the CG XCPM Magnus force center of pressure, calibers from center of gravity Subscripts

Initial condition

f Final condition

2 Indicates second order coefficient of Maple-Synge polynomial expansion

Superscript

Secant slope

Il

ABSTRACT

An extensive study of the aerodynamic characteristics of the 4.2", M329A1E1 Mortar Projectile has been conducted. A spectrum of yaw levels up to 40° and Mach numbers from 0.55 to 1.025 were ered in the Ballistic Research Laboratories (BRL) Transonic Radicity. A Magnus wind tunnel test in the Ames 12° Pressure Wind Tunnel involved boom and boattail effects on Magnus as well as static forces and moments. Mach numbers from 0.3 to 0.95 and angles of attack from 0° to 30° (for a Mach number of 0.3) and 0° to 20° (for the higher Mach numbers) were considered. Shell instrumented with yaw sondes were fired at the Wallops Island Facility of NASA. The theoretical differential equation of motion then was fitted to the resulting single plane angular motion data.

INTRODUCTION

The M329A1E1 projectile is the result of an accelerated product improvement program with the objective to provide a replacement for the M329A1 projectile. Because of the accelerated nature of the program only the improvements which are within the current state of the art have been incorporated. Figures 1 and 2 are drawings of the M329A1E1 and the M329A1 projectiles. The subcaliber cylindrical sections contain the ignition cartridge; they appreciably affect the aerodynamic characteristics of the shell.

The 4.2", M329Al has been in use since 1940. Its extension to the cartridge housing was part of an attempt to upgrade the system performance by increasing the chamber volume and enabling the use of larger charges. The M329Al has a history of occasionally erratic flights, the propensity for which increases when the extension to the cartridge housing is present. This extension generates a larger Magnus moment than the original short boom configuration and can lead to dynamic instabilities.

Several improvements have been incorporated into the M329A1E1 design. The drag is decreased by replacing the square base of the M329A1 by a 0.65 caliber boattail and adding a longer windshield. A fixed pre-engraved rotating band has been incorporated into the new design in an attempt to improve the spin performance. A constant chamber volume propellant system makes it possible to eliminate the extension to the cartridge housing.

Cumulatively, these configurational changes mean an improvement of the M329A1E1 in both high and low range capability.

TEST FACILITIES

BRL Transonic Range

The M329A1E1 projectile was fired at subsonic and low transonic velocities in the Ballistic Research Laboratories (BRL) Transonic Range Facility described in Reference 1.

NASA Ames 12' Pressure Wind Tunnel

The Ames 12 Pressure Wind Tunnel is a variable-density, lowturbulence tunnel that operates at subsonic speeds up to slightly less than Mach number 1.0. It is powered by a two-stage axial-force fan driven by electric motors. Airspeed in the test section is controlled by variation of the rotational speed of the fan. Eight fine mesh screens in the settling chamber together with the large contraction ratio of 25 to 1 provide an airstream of exceptionally low turbulence. A special mounting drive system was available for angles of attack over 20°. Figure 3 is a plot of the operating characteristics of this wind tunnel. The full scale test configurations and strain gage balance beams were constructed by the Supersonic Wind Tunnel Branch of BRL. The two beams prepared for the test are SB228A and backup beam SB228B, but only the former was used. They are five component strain gage balances, each of which has two pitch gages and three yaw gages specifically designed for the forces and moments anticipated in this test. The exterior of the model consisted of three basic parts.:

- a. Ogive and cylindrical section
- b. Tail section (square base or boattail)
- c. Boom

Model designations are as follows:

Designation	Drawing Number	<u> Item</u>
NB	SSK2590B - 1 SSK2590A	M329A1E1 nose and cylindrical body
T_{1}	SSK2590 - B2	Boattail on the aft 0.65 calibers of the model
T ₂	SSK2590 - B3	Square base (same length as boattail)
C,	SSK2590 - B4	Cartridge housing

 C_o NBG_1C_1

No cartridge housing

Configuration NBT₁C₁ with grit on the last inch of cartrdige housing

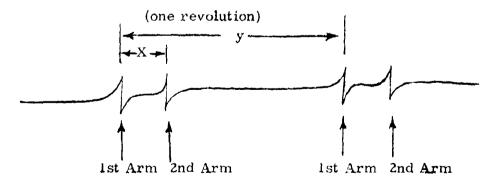
The M329A1E1 is designated by NBT₁C₁. The configuration shown in Figure 4 is NBT₁C₀.

Performance Flight Tests

Performance flight tests have been conducted, the majority of them at Yuma Proving Ground. Firings in January 1969 involved two preliminary designs with different boattail lengths, which will be called the "long" boattail (0.85 calibers) and the "short" boattail (0.65 calibers). The objective of subsequent firings was the development of an effective rotating band and obturator. Camera coverage was requested for some of these rounds to obtain a yaw record over and past the peak. All rounds were fired from the M30, 4.2 inch Mortar tube, which has a progressive twist resulting in one turn of the projectile in 20 calibers of linear travel.

Yaw Sonde Program

Yaw sondes and their use are fully described in Reference 2. Briefly, a yaw sonde fuze consists of two strips of photovoltaic material arranged to intercept a ray of light which is passed through a pin hole in the side of the fuze body. The strips are placed on a plane containing the axis of symmetry of the projectile in the form of an inverted V. As the projectile rotates in flight a sun ray impinges on each arm of the V. The resulting signals which take the form;



are transmitted to a recording station. As the projectile yaws while rotating, the sun ray moves up or down the axis of the projectile. Thus the ray takes a shorter or longer time to cross from the first to the second arm of the V. Therefore, as the yaw angle and the spin rate decay various values of x and y are obtained. Having previously calibrated the yaw sonde with a fixed light source and special angle measuring devices, a graph of sun angle vs a function of x and y can be determined. This calibration is then applied to the signals obtained from free flight and a plot of sun angle vs time of flight is obtained.

The yaw sonde firings of the M329A1E1 projectile were a joint effort of the BRL at Aberdeen Proving Ground and Picatinny Arsenal. Wallops Island was chosen as the site of the test, primarily because of the quality of instrumentation available there. Tracking instrumentation included a MPS-19 radar.

Six yaw sonde-equipped M329A1E1 rounds were fired on 22 and 23 October 1969 under the conditions listed in Table 1. Since the yaw sonde package is lighter than the standard fuze, the physical characteristics of the projectile differ from the standard M329A1E1 projectile. They are also listed in Table 1. Figure 5 shows a yaw sonde-equipped M329A1E1 projectile.

EXPERIMENTAL PROCEDURE

BRL Transonic Range

For small yaw angles the BRL Transonic Range test was conventional. However, to reproduce the rather large yaw levels (due to yaw of repose) which have been measured for low velocity and high quadrant elevation fire, a four-kilogram Lexan cylinder was placed 75 centimeters from the muzzle. By glancing the projectile off this cylinder, yaws in excess of 30° were produced without damage to the shell.

NASA Ames 12' Pressure Wind Tunnel

The preparations and techniques used for obtaining Magnus data in wind tunnels are outlined in Reference 3. The Reynolds number-Mach number combinations at which data was recorded in the Ames 121 Pressure Wind Tunnel are plotted in Figure 3. Where possible, the stagnation pressure was atmospheric. Reynolds numbers above and

below this value also were considered. When tunnel conditions were proper and the Mach number correct, the angle of attack was set and the model spun-up to approximately 12,000 rpm. As it was allowed to spin down, readings from all gauges were taken as a function of spin rate on Mosley X - Y Recorders. For the pitch recorders zero moment was positioned in a convenient place on the chart while static tunnel conditions existed. The tunnel then was put into operation and the model rotated through the angle of attack range. For the yaw recorders zero moment was extrapolated back to the point of zero spin rate. Figures 6 and 7 are typical raw data charts. After all Mach number and Reynolds number combinations had been run, a special mounting drive system was used to obtain data to 30° for a Mach number of 0.3 and the Reynolds numbers involved. Considerable overlap was allowed in order to maintain the continuity of the reduced data. A sand band of No. 20 grit was attached to the last inch of the boom for two Mach number - Reynolds number combinations to aid in the investigation of subcaliber after body effects. Mach numbers of 0.3 and 0.55 and their respective Reynolds numbers of 1.7 x 106 and 2.9 x 106 were involved.

Performance Flight Tests

Flight tests at Yuma Proving Ground were established to examine the performance at high and low charges as well as high and low quadrant elevations. Muzzle velocity was determined by use of velocity coils and magnetized shell. Range and deflection were measured by spotting personnel. In addition, for some rounds, cameras were positioned at the muzzle for spin and yaw measurements and underthe trajectory peak of a low charge, high quadrant elevation flight for a determination of the yaw of repose (Fig 8).

Yaw Sonde Program

In setting up the yaw sonde test, the tube was positioned 1,300 ft from the radar along an azimuth of 143°. Line of fire of the low charge rounds was along an azimuth of 115°, while high charge rounds were along 130°. The muzzle velocity of each round was measured by a Fastax camera. Trajectory data, including range, altitude, and deflection, were obtained from an MPS-19 tracking radar for each projectile.

DATA REDUCTION TECHNIQUES

BRL Transonic Range

The methods used in the analysis of the transonic range data are documented in References 4 and 5. The angular orientation as well as the position of the projectile in the range are fitted to a closed form solution of the linearized equations of motion by differential correction and least square fits. If a nonlinear system is indicated, the total results must be reviewed on a quasi-linear basis to determine the aerodynamic coefficients.

NASA Ames 12' Pressure Wind Tunnel

Reduction of wind tunnel data is fairly straightforward; however, a determination had to be made concerning the extent of sting interference on the contribution of the boom to Magnus forces and moments. The circulatory flow about the boom itself was felt to be a stronger Magnus generator than boom end effects; and since the sting was not expected to have greatly disturbed this flow (Refs 6, 7, and8) data could be considered meaningful. Wind tunnel data reduction was performed by two independent units, the Data Reduction Section at Aberdeen Proving Ground, and a reduction unit at Picatinny Arsenal. At Picatinny Arsenal a computer program was developed to reduce readings from the Mosley recorders, shift the resulting force and moment coefficients to pass through zero at zero angle of attack, and plot the shifted coefficients. A 5th - 11th order fit (depending on the data) is represented by the solid line on each plot. Secant slopes of the Magnus and pitching moment coefficients vs angle of attack have been plotted for the reduced data points as well as the higher order fits. All moments and centers of pressure are referenced to the center of gravity (2.48 calibers from the nose) and Magnus force and moment coefficients were calculated using the nondimensional spin parameter pd/2V.

Performance Flight Tests

For the most part performance flight tests yielded only statistical data. Plots of range and deflection vs muzzle velocity help to indicate short rounds, and computation of standard deviations of range, velocity, and deflection are a means of comparing performance of the M329A1E1 with the M329A1. Spin rate calculations were made from

camera coverage at the muzzle for specially painted shell. Yaw histories were measured directly from the muzzle and the downrange camera records, and are discussed in the Section "Experimental Procedures/Performance Flight Tests".

Yaw Sonde Program

Raw data from the yaw sondes was transformed into sun angle and time of flight data and placed on magnetic tape by BRL. These values were then plotted (sun angle vs time of flight) with the aid of the high speed computer. The method of Chapman and Kirk (Ref 9) and a specially modified six degree of freedom trajectory program were used in an effort to reduce the angular motion output of the yaw sonde to aerodynamic coefficient form. Briefly, the size of the section of data to be fitted by the method of Chapman and Kirk was limited by the change in Mach number, since it is not yet one of the fitted parameters. This allowed Mach number variation was established by plotting wind tunnel and range data vs Mach number and then limiting the

$$\frac{\Delta C_{m_{\alpha}}}{\Delta \text{Mach No.}}$$
, $\frac{\Delta C_{m_{q}}}{\Delta \text{ Mach No.}}$, $\frac{\Delta C_{n_{p_{\alpha}}}}{\Delta \text{ Mach No.}}$

to $\pm 2\%$ of the value at the average Mach number of the section. Certain differential equations of angular motion were then fitted to these sections of data. Both linear and nonlinear $C_{m_{\chi}}$, $C_{m_{\chi}}$, and $C_{np_{\chi}}$ were considered.

PRESENTATION OF TEST RESULTS

BRL Transonic Range

Data from the BRL transonic range is presented in Table 2. Coefficient values within selected Mach number ranges have been plotted vs angle of attack (Figs 9, 10 and 11).

NASA Ames 12! Pressure Wind Tunnel

The results from the Ames 12' Pressure Wind Tunnel have been plotted vs angle of attack. As was previously mentioned, the solid line through the data points represents a 5th - 11th order fit.

Figures 12 through 157 are plots of normal force coefficient, pitching moment coefficient, and normal force center of pressure vs angle of attack. Several nondimensional spin rates and Reynolds numbers are included for each Mach number.

Early in the test it was noted that the output on the forward pitch recorder was of poor quality. The difficulty was traced to a crushed lead wire to the forward pitch recorder. Normal force data on configuration NBT1C1 taken at Mach numbers of 0.3 and 0.55 at various Reynolds numbers was affected by the faulty lead wire, could not be rerun, and is not reported here.

Magnus force coefficient, Magnus moment coefficient and Magnus force center of pressure are plotted in Figures 158 through 333.

From this data, secant slopes of pitching moment and Magnus moment vs angle of attack have been calculated and are presented in Figures 334 through 357. The symbols on slope plots represent C_{m_α} 's and C_{np_α} 's for each data point. The solid line is the calculated C_{m_α} or C_{np_α} vs angle of attack from the fit to the original data. Figures 358 through 367 show the relationship of C_{m_α} and C_{np_α} to Mach number, $\frac{pd}{2V}$, and Reynolds number. Agreement between the two independent reductions of this data is excellent. An average deviation of $\pm 2\%$ was found in the check cases.

Performance Flight Tests

Results from performance flight tests include some plots displaying range vs velocity performance (Figs 368 and 369).

In addition, some of the film records were translated into pitch and yaw data at various points throughout the trajectory (Figs 370 through 374). At the time of these firings, the rubber obturator had failed to separate from the projectile at low charges. Figure 375 is a photograph of the M329A1E1 soon after exiting the muzzle at a velocity of 255 feet per second. The obturator is clearly on, although displaced from its original setting, undoubtedly causing adverse aerodynamic loads. This displacement is caused by the force of the muzzle gases as they pass over the projectile shortly after it exists the muzzle.

At high charges, the obturator is broken by the blast; but at some intermediate charges it is possible that it will be forced to a position anywhere along the projectile.

DISCUSSION AND ANALYSIS (BRL Range and Ames Wind Tunnel)

The following discussion and analysis directly compares results from the BRL Range and the Ames Wind Tunnel. Yaw Sonde results will be discussed separately, due to the unique methods by which they are obtained and the care with which they must be interpreted.

Pitching Moment Coefficient Derivative ($C_{m_{\alpha}}$)

Referring to Figure 376, the range, wind tunnel and SPINNER (Ref 10) agree well for this parameter. The increase in the transonic region is partially due to an increase in the normal force coefficient and largely due to a forward (meaning towards the nose) movement of the normal force center of pressure with increasing Mach number (Fig 376). A plot comparing $C_{\rm m_{\infty}}$ for the three configurations tested in the Ames Wind Tunnel appears as Figure 358. The Reynolds number effects are small (less than 3%). $C_{m_{\odot}}$ is about 44% lower for the square base configuration NBT₂C₁. Although the normal force of NBT2C1 is greater, the center of pressure is considerably closer to the center of gravity than NBT1C1. At the lower Mach numbers the pitching moment coefficient derivative of NBT₁C₁ is greatest because its normal force center of pressure is slightly more forward of the center of gravity than for NBT1C0. The normal forces are the same. At the high Mach number (0.85 - 0.95) NBT₁C₁ has an 8% lower normal force than NBT 1Co. Its center of pressure remains more forward of its center of gravity. Thus $\ensuremath{\text{NBT}_1C_1}$ and $\ensuremath{\text{NBT}_1C_0}$ have nearly the same $C_{m_{\Omega}}$'s at M = 0.85 and 0.95. The effect of angle of attack on $C_{m_{\infty}}$ is most clearly demonstrated at M = 0.305 (Figs 340 and 342). This decrease in $C_{\mathrm{m}_{\gamma}}$ is due to a rearward movement of the normal force center of pressure with an increase in angle of attack. For the other Mach numbers, the angle of attack ranges are not nearly so large, and $C_{\mathbf{m}_{\alpha}}$ tends to remain nearly constant. A linear approximation up to $10^{\circ 7}$ appears to be an accurate one here.

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The following discussion and analysis directly compares results from the BRL Range and the Ames Wind Tunnel. Yaw Sonde results will be discussed separately, due to the unique methods by which they are obtained and the care with which they must be interpreted.

Pitching Moment Coefficient Derivative ($C_{m_{\alpha}}$)

Referring to Figure 376, the range, wind tunnel and SPINNER (Ref 10) agree well for this parameter. The increase in the transonic region is partially due to an increase in the normal force coefficient and largely due to a forward (meaning towards the nose) movement of the normal force center of pressure with increasing Mach number (Fig 376). A plot comparing $C_{\mathbf{m}_{\alpha}}$ for the three configurations tested in the Ames Wind Tunnel appears as Figure 358. The Reynolds number effects are small (less than 3%). Cm, is about 44% lower for the square base configuration NBT₂C₁. Although the normal force of NBT2C1 is greater, the center of pressure is considerably closer to the center of gravity than NBT1C1. At the lower Mach numbers the pitching moment coefficient derivative of NBT1C1 is greatest because its normal force center of pressure is slightly more forward of the center of gravity than for NBT₁C₀. The normal forces are the same. At the high Mach number (0.85 - 0.95) NBT₁C₁ has an 8% lower normal force than NBT₁C₀. Its center of pressure remains more forward of its center of gravity. Thus NBT1C1 and NBT1C0 have nearly the same $C_{m_{cl}}$'s at M = 0.85 and 0.95. The effect of angle of attack on $C_{m.}$ is most clearly demonstrated at M = 0.305(Figs 340 and 342). This decrease in $C_{\mathrm{m}_{\alpha}}$ is due to a rearward movement of the normal force center of pressure with an increase in angle of attack. For the other Mach numbers, the angle of attack ranges are not nearly so large, and $C_{\mathbf{m}_{\alpha}}$ tends to remain nearly constant. A linear approximation up to 10° appears to be an accurate one here.

Figures 193, 204, and 218 show reasonably good agreement of the BRL Range and the Ames Wind Tunnel data for this difficult-to-measure parameter. Of particular interest is the fact that the range as well as the wind tunnel data shows a negative C_{np_0} at Mach number 0.567 and 9° angle of attack. The effect of this on stability will be discussed in a later section.

The point should here be made that small force and moment Magnus data, normally at the lower angles of attack, may contain considerable percentage error; however, relative magnitudes and consistent trends are of value. $C_{\mathrm{np}_{\gamma}}$ versus Mach number for the three configurations tested in the Ames Wind Tunnel are shown in Figures 359 and As Mach number increases in the transonic region $C_{n_{\mathbf{p}_{\alpha}}}$ for Configuration NBT₁C₁ peaks sharply due to a sharp rise in Magnus force. NBT2C1, however, behaves quite differently, remaining nearly constant throughout the same region. It is not uncommon for square base projectiles to peak at higher Mach numbers than boattail projectiles. The boomless Configuration NBT₁C₀ has a lower C_{np} throughout most of the Mach number range tested, supporting the belief that the boom is a Magnus generator even at low angles of attack. Figures 361 and 367 show the variation of $Cn_{\mathbf{p}_{T}}$ with both pd/2V and angle of attack. At the lower angles of attack and pd/2V's, $C_{n_{D\alpha}}$ tends to be negative. This is primarily due to a positive Magnus force in this region of somewhat uncertain data. The trend, however, is consistent throughout the entire Mach number range.

Drag Coefficient (C1)

The drag coefficient, for small yaws, as measured in the BRL Range, agrees well with the SPINNER data bank (Fig 317). Six-degree of freedom trajectory simulations using such drag data closely agree with full range firings at Yuma Proving Ground.

 $(C_{m_Q} + C_{m_{\tilde{\alpha}}^*})$ as determined by the BRL Range appears constant above 4° for Mach numbers below 0.543. Between M = 0.638 and 0.867, $C_{m_Q} + C_{m_{\tilde{\alpha}}^*}$ is constant above 2° (Figs 11 and 380). Below these angles of attack, $C_{m_Q} + C_{m_{\tilde{\alpha}}^*}$ becomes less negative, indeed, has been measured as positive at some low angles of attack. This could be caused by a dominance of the $C_{m_{\tilde{\alpha}}^*}$ term.

Gyroscopic Stability

Referring to Figure 381, the gyroscopic stability factor of the M329A1E1 remains within acceptable bounds throughout the Mach number range. The improvement over the M329A1 Projectile also is clear. Simulating -26.3°F lowers the gyroscopic term over 16% but it still remains well within the region of gyroscopic stability.

Dynamic Stability

Nonlinear damping factors, $\lambda_{1,2}^*$ from the quasi-linear theory, were calculated using data from the Ames Wind Tunnel, and plotted vs angle of attack in Figures 382 through 386. These parameters give an insight into what can be expected in terms of angular motion as the projectile traverses a trajectory. One may qualitatively explain the motion of a low charge high quadrant elevation round with the aid of Figure 382 in the following way: As the projectile exits the muzzle, it receives an initial disturbance resulting in an average maximum yaw of 1 or 2 degrees. At this point the precessional mode appears to be slightly undamped. Of course, due to the error in the data and the sensitivity of $\lambda^{*}_{1,2}$ to Magnus and damping, the precessional mode may be slightly damped. On the way to the trajectory peak a rather large yaw of repose appears and carries the projectile into a region where the precessional mode is heavily damped while the nutational mode is strongly undamped. From here on it becomes a race up to the ground impact, as the K₁ arm grows and the K₂ arm damps. The damping factors are functions of Mach number and angle of attack (Figs 382 through 386). As the Mach number decreases, there are changes in the size of the small angle precessional limit cycle until eventually a nutational limit cycle will appear.

Similarly, if the projectile is disturbed upon launch from the muzzle to an angle of attack of 12° , below M = .75, the angular motion will diverge due to a nutational instability. The result of this is, of course, a short range.

DISCUSSION AND ANALYSIS (Yaw Sondes)

Many attempts have been made to fit the differential equation of motion to the angular motion data obtained from the yaw sonde. While performing these fits, in addition to holding the coefficients $C_{m_{\alpha}}$, $(C_{m_{q}} + C_{m_{\alpha}})$, and $C_{n_{p_{\alpha}}}$ constant, various combinations of higher order terms were considered. Convergence of the equation of motion to the data was achieved for many of these combinations resulting in some reasonable fits. Some of the coefficients which generated such motion are, however, not in good agreement with those of the wind tunnel and transonic range. Among the questions raised due to these disappointing results are:

- 1. What accuracies are needed in yaw sonde manufacture and calibration?
- 2. How sensitive is the motion and thus the fit, to rather large nonlinearities in the coefficients?
- 3. For a given set of yaw sonde sun angle data, radar data, and projectile physical parameters, how accurately can we separate and determine the Magnus and damping moments?

While we are not ruling out fitting the equation of motion to yaw sonde data as a powerful tool in stability coefficient determination, the results of our analysis do not, at this time, merit publication until additional efforts in the area can answer some of these important questions. A qualitative discussion of the results from the yaw sonde follows.

Figures 387 through 392 show solar aspect angle data from the yaw sonde for a projectile fired at a 45° quadrant elevation and two projectiles fired at a 60° quadrant elevation. All three projectiles had a muzzle velocity of approximately 1050 feet per second.

Referring to the damping factor plots (Figs 382 through 386) one can see that the precession arm will undamp up to two degrees at a Mach number of 0.95 and up to almost five degrees for a Mach number of 0.85. We can expect, therefore, that the precessional arm should be slightly undamped near the muzzle. This is the case for the three examples shown. The initial magnitude of the nutational arm may be attributed to the muzzle disturbance. As the Mach number decreases on the up leg of the trajectory the precession damps as shown by the damping factors of Figures 382 through 386, and the nutational arm can be expected to grow to one or two degrees. This behavior will be enhanced by the increase in C_{npa} due to the increased pd/2V in this region. The precession damps as the peak of the trajectory is traversed due to the decreasing Mach number. On the down leg of the trajectory, the combined effects of the yaw of repose, the Mach number increase, and the pd/2V decrease, cause the precessional arm to reappear.

CONCLUSIONS AND RECOMMENDATIONS

The M329A1E1 has adequate damping characteristics and therefore adequate stability throughout its Mach number regime. A problem area appears in the low charge and high quadrant elevation firings due to a rather large gyroscopic term and resulting yaw of repose. When fired with a tail wind this problem becomes greater, and fuze functioning may be affected due to impact at large yaws. In addition, the rubber obturating band has been observed to remain with the round at this minimum charge. Such an occurrence will result in a decrease in accuracy and an unpredictable ground impact angle.

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TABLE 1

Physical characteristics and launch conditions of M329A1E1 yaw sonde rounds	Center of Gravity (inches from base)	!		6.432	6.437	6.427	6.43	
9AlEl yaw	Weight (1b)	\$ 8 1 1	1 1	21.0	21.01	20.96	21.0	
litions of M32	$(1b - in.^2)$		† † †	386.7	387.9	385.8	386.2	
id launch cond	^{Ix} (1b - in. ²)	!	# # # #	50.89	50.84	50.84	50.93	
istics an	Q E (deg)	09	09	45	45	09	09	
al character	V Muzzle (fps)	267	255	1052	1058	1064	1052	
Physic	Round No.	4729	4731	4737	4738	4739	4740	

22.2

Standard M329A1E1

TABLE 2

Ballistic Research Laboratories' range coefficients

	mî	T	بهادسائل													-
	(10^3)		6077	. 0328	2253	1417	.3838	0894	1409	0043	1991	1913	2092	1328	- 140g	0047.
	(103)	1900	1 6	/162.	.0017	.0344	. 05.13	0352	0211-			.0239	0469	0493	0943	
	Sg	<u>س</u>	,	7.04	40.7	7.4.	7.60	7 55 C	2.5	26.2	2.40	3.03	2.43	2.40	2.38	
	Cmc + Cme	-2.5852	- 2 a	-3 BOE 7	7000 -	10 3487	-1.3238	-3.9880	-3 .0283		75.7035	-1.3454	-3.7596	-2.3079	-3.2853	-3.0522
	رير	6433	0.666	5232	7781	-1.0825	9233	5005	2408	4720	י ני	7977	.5106	8910	7027	.0635 -1.0305
	c _n		1803	.3710	.1282	-1.0006	.0404	.1686	1034	.2856	.2265	00.96	£007.	1104	.1223	.0635
	C _P	3.3172	3.7357	4.6655	3.9212	3.7364	3.9031	3.8904	3.9469	4.1712	3.2541	700	99/0.5	3.7275	3.5742	4.8470
	ď	1.6720	1.4035	6.9987	1.3353	1.3287	1.3305	1.3741	1.4063	1.2307	1.5599	1.6291		1.5295	1.5725	7166.
	om U	2.5441	2.9755	3.0460	3.0787	2.8179	3.0436	3.1257	3.2735	3.1450	2.5558	3.1980		3.2302	3.2737	3.2025
L	G -	.2712	.1741	.1118	.1182	.1109	.1236	.1277	1031	.1185	.2160	1195		. 1075	1093	.1962
	ig	15.53	8.96	2.31	3.27	1.38	3.45	4.42	69.0	3.48	14.17	3.29	33	n .	ਦ ਲ ਪ	1.28
	MACH NO.	.523	. 543	.517	-527	.425	.435	.638	.634	.727	.483	.720	277	·	.775	797.

TABLE 2 (Cont'd)

2 (10 ³)	1607	1997	-
1 (10 ³)	2.3204001607	2.2207401997	
89	2.32	2.22	
MACH NO. 28 CD CM. CP. Cnp. Cyp. Cmq + Cm. Sg 1 (10 ³) 2 (10 ³)	3.90 .1252 3.3426 1.2097 4.3017 .20473038 -3.0189	.1270 -3.7254	
$c_{ m y_{ m p}}$	3038	.1270	
C _n	.2047	2.90 .1193 3.3211 1.9091 3.3552 .2021	0
C _P M	4.3017	3,3552	7,77
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8 U	3.3426	3.3211	000
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æ	3.90	2.90	,
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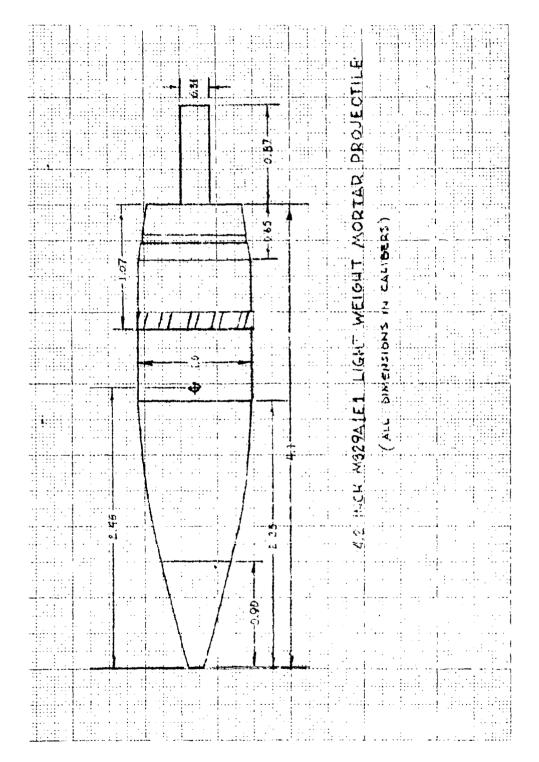


Fig : 4.2" M329A1E1 mortar projectile (all dimensions in calibers)

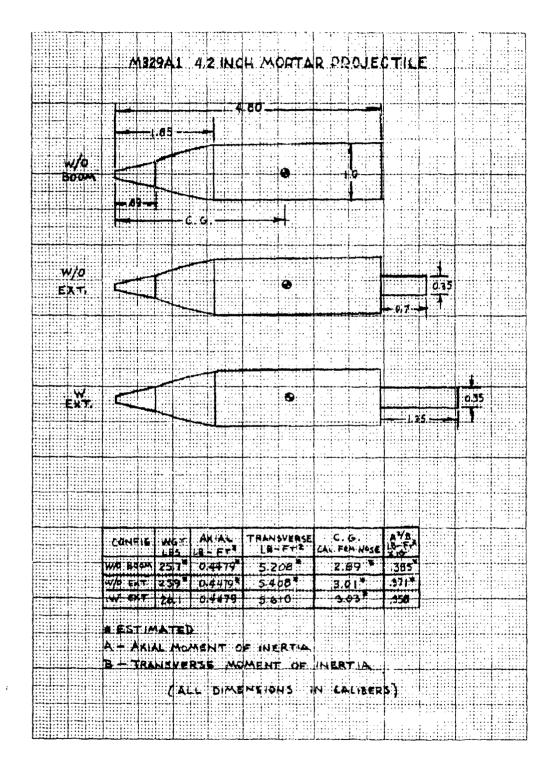


Fig 2 4.2" M329A1 projectile

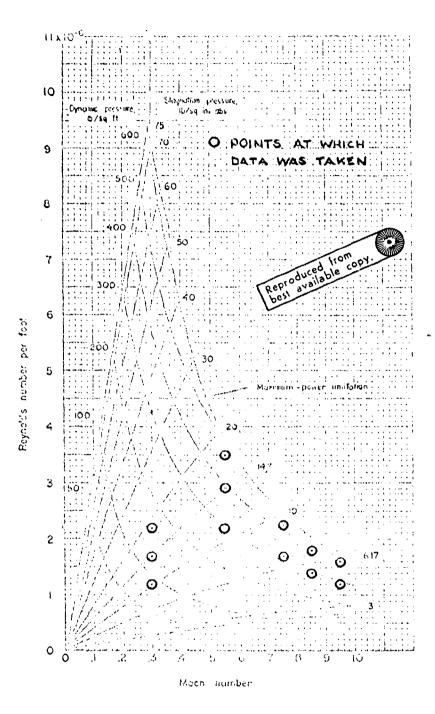


Fig 3 Operating characteristics of the Ames 12* pressure wind tunnel (PWT)

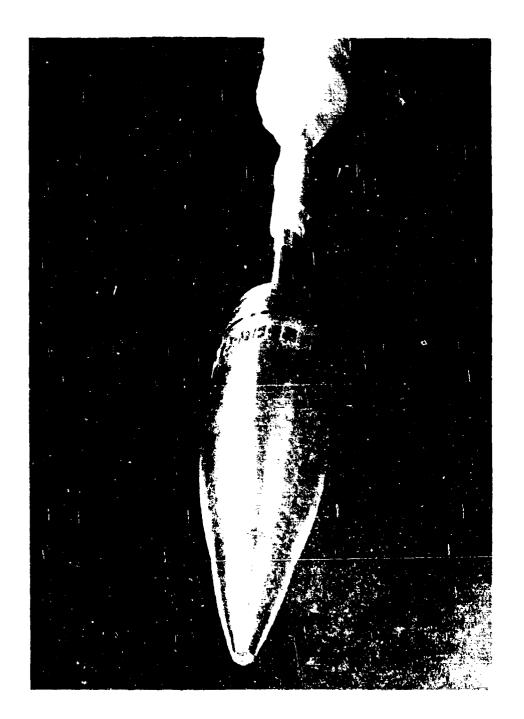


Fig 4 Configuration NBT₁C_o mounted in 12' PWT

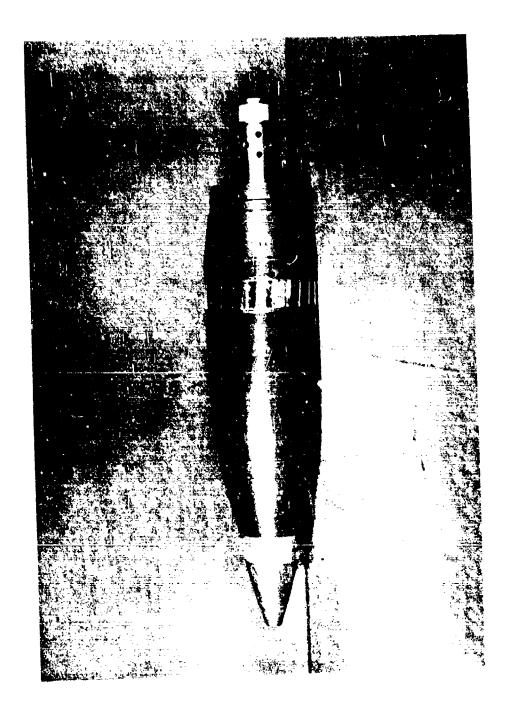
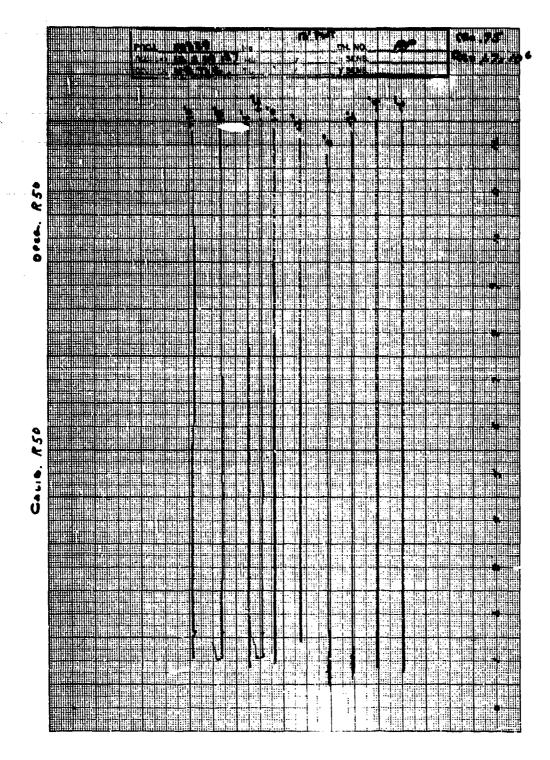
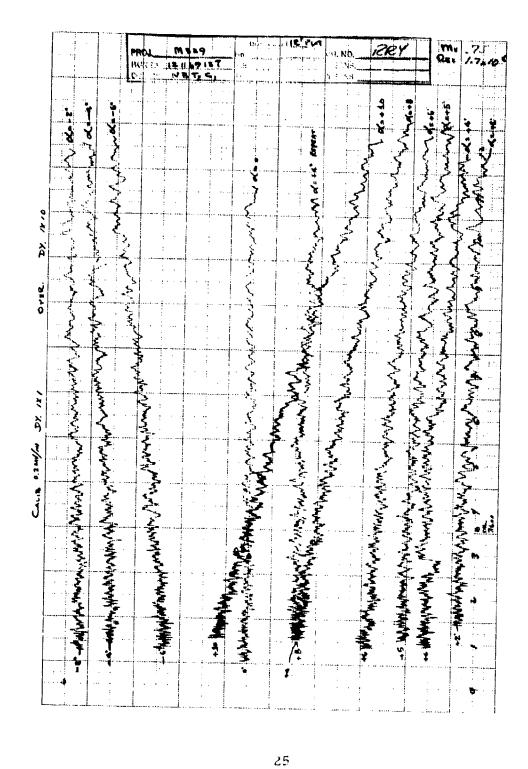


Fig 5 M329A1E1 projectile equipped with yaw sonde



Raw data chart from 12' PWT (pitch gauge readings vs model rpm)



Raw data chart from 12' PWT (yaw gauge readings vs model rpm) Fig 7

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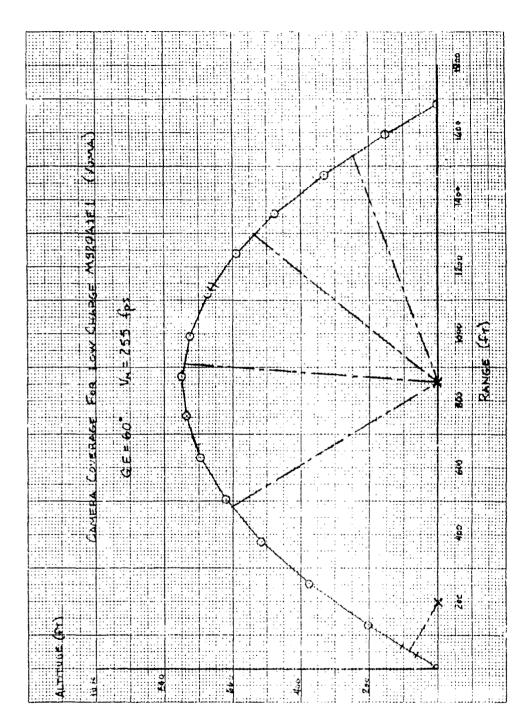


Fig 8 Camera coverage for low charge high quadrant elevation firing of M329AlE1 projectile at Yuma Proving Ground

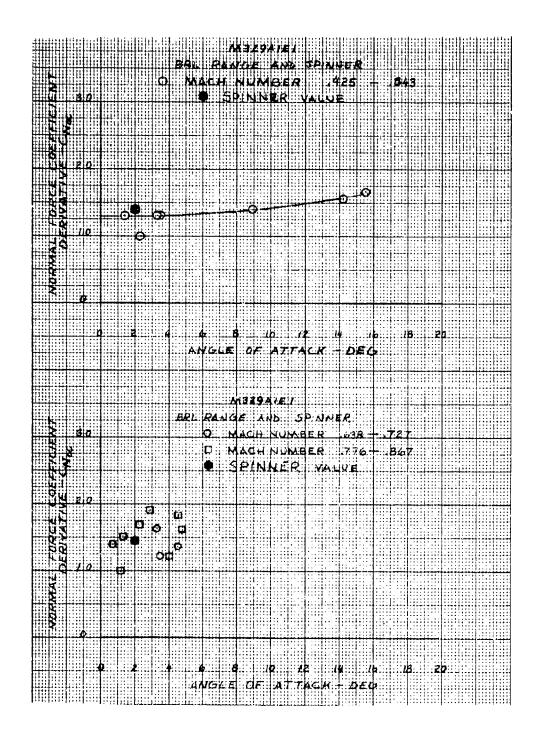


Fig 9 Normal force coefficient derivative vs angle of attack (BRL transonic range)

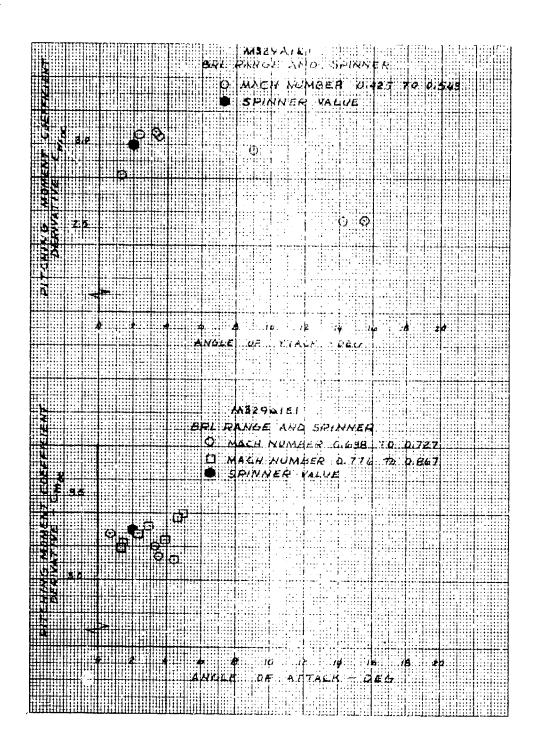
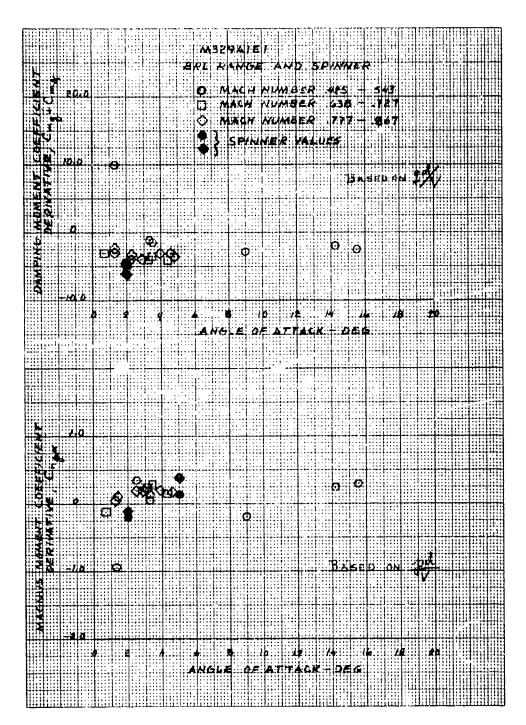


Fig 10 Pitching moment coefficient derivative vs angle of attack (BRL transourceunge)



Pitch damping coefficient ($Cm_Q + Cm_{\tilde{c}}$) Magnus moment coefficient derivative vs angle of attack (BRL transonic range) Fig 11

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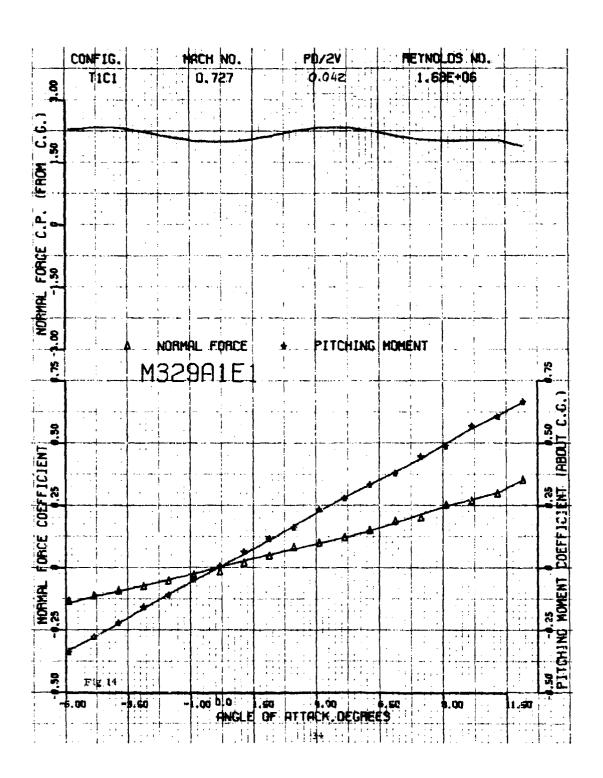
Figures 12 through 157

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Normal force coefficient, pitching moment coefficient, and normal force center of pressure vs angle of attack.

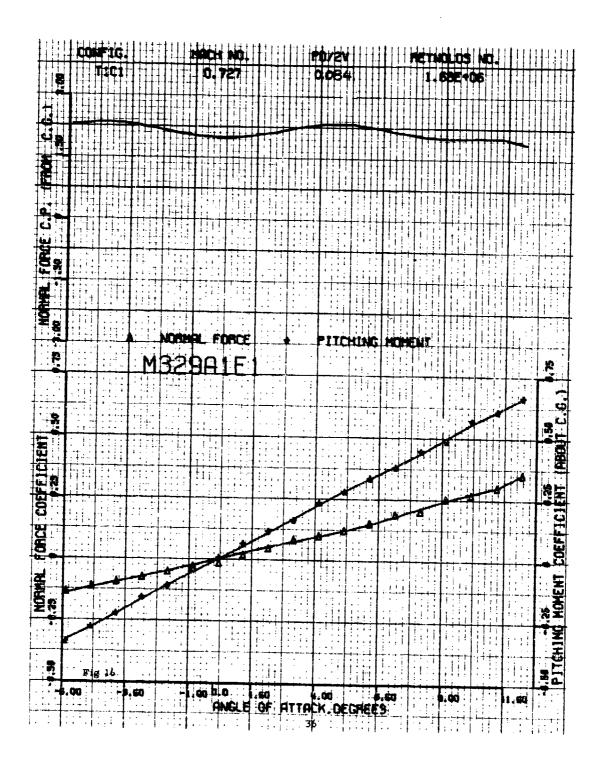
(Includes several configurations, Mach numbers, pd/2V's and Reynolds numbers [12' PWT].)

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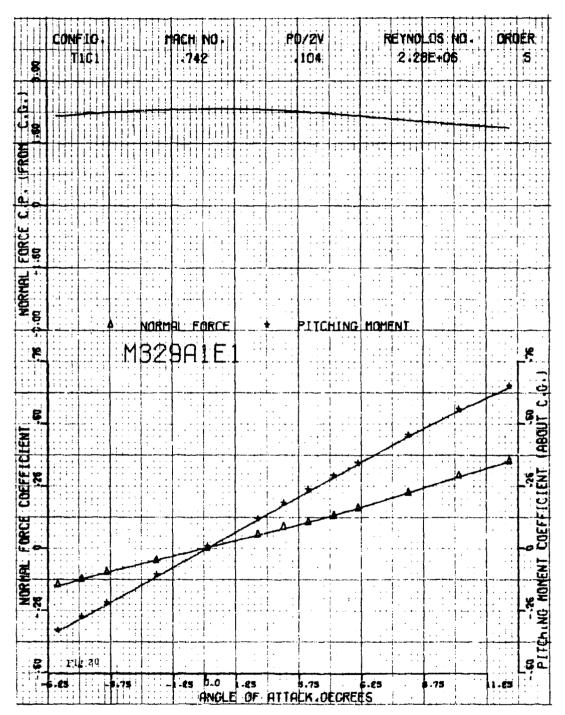


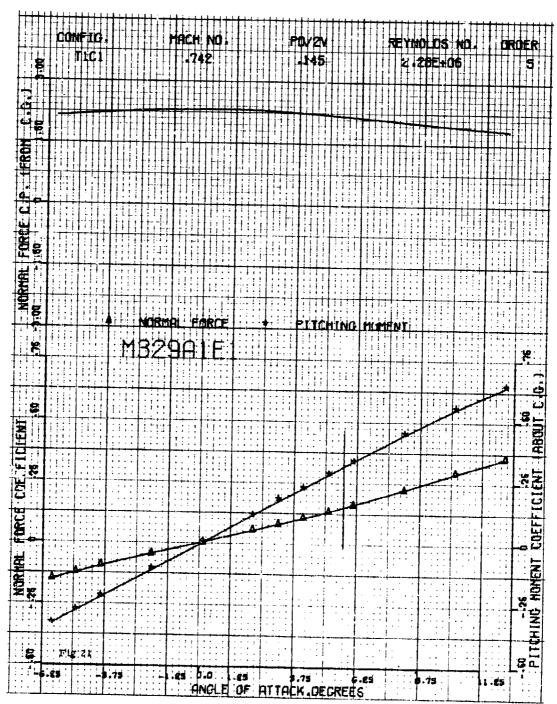
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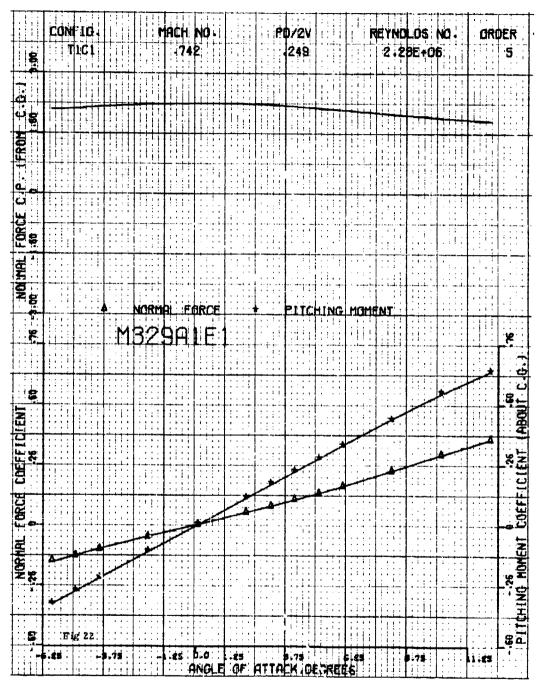
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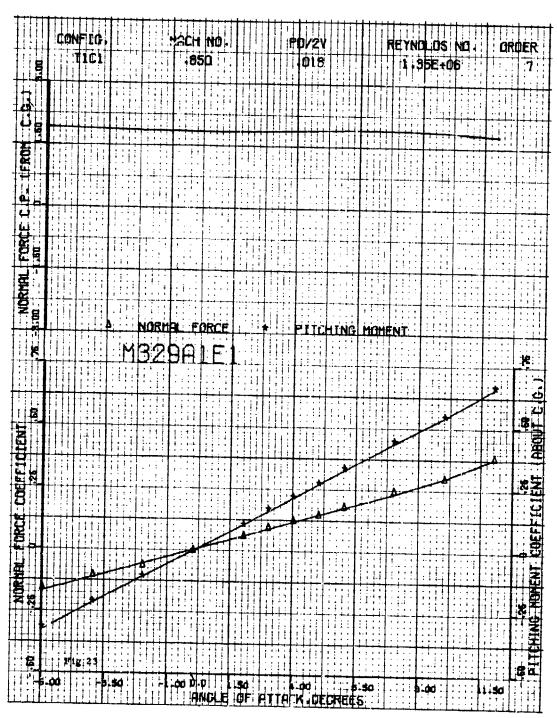


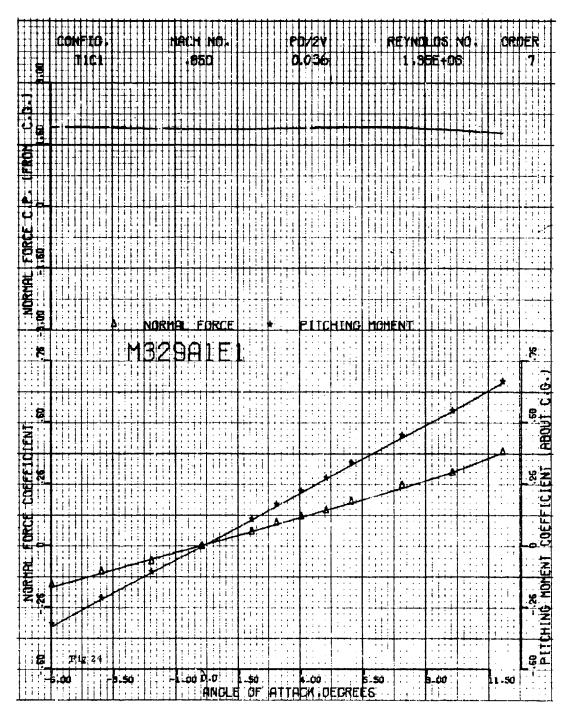
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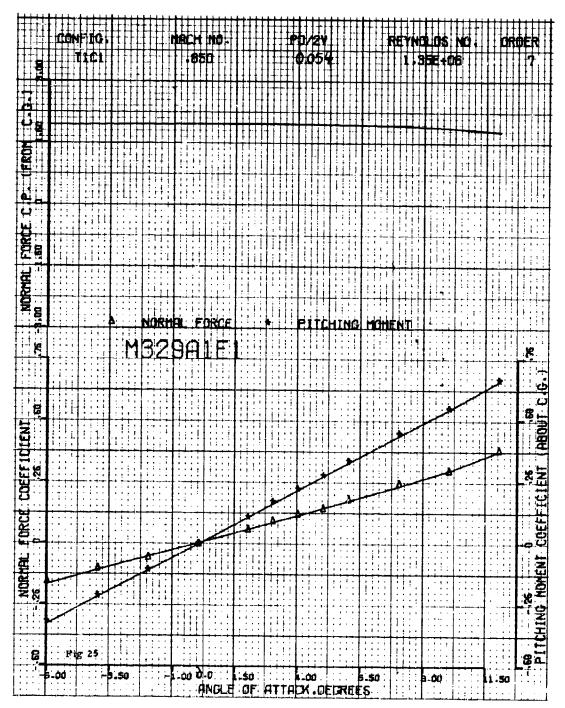




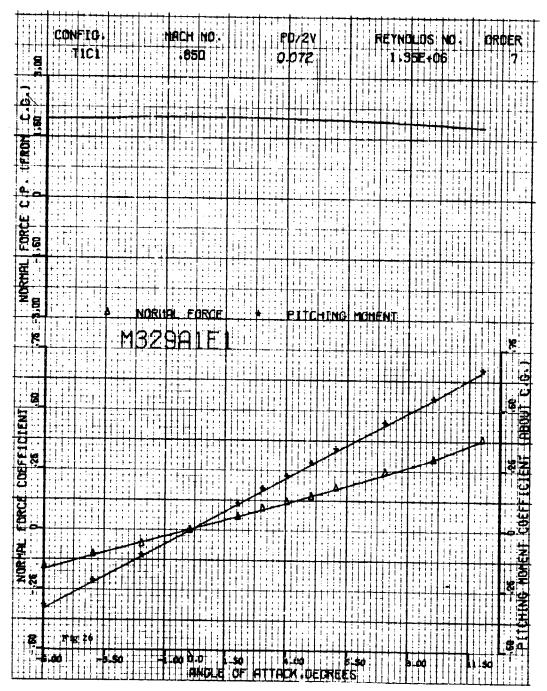
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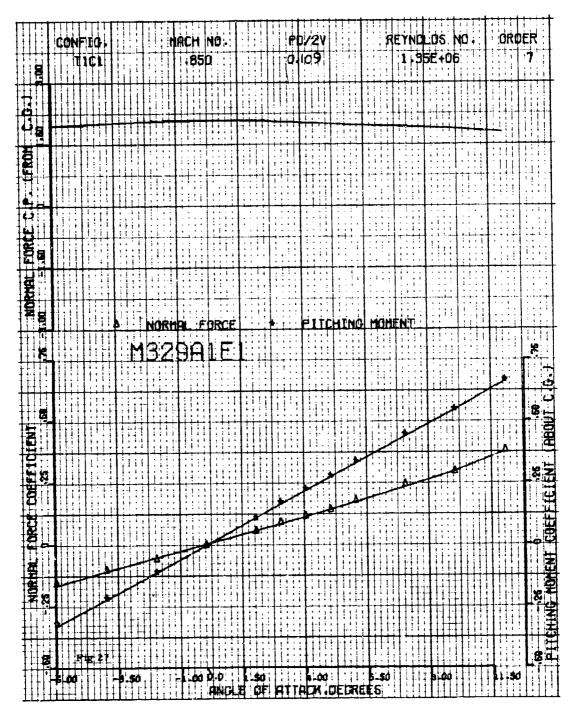




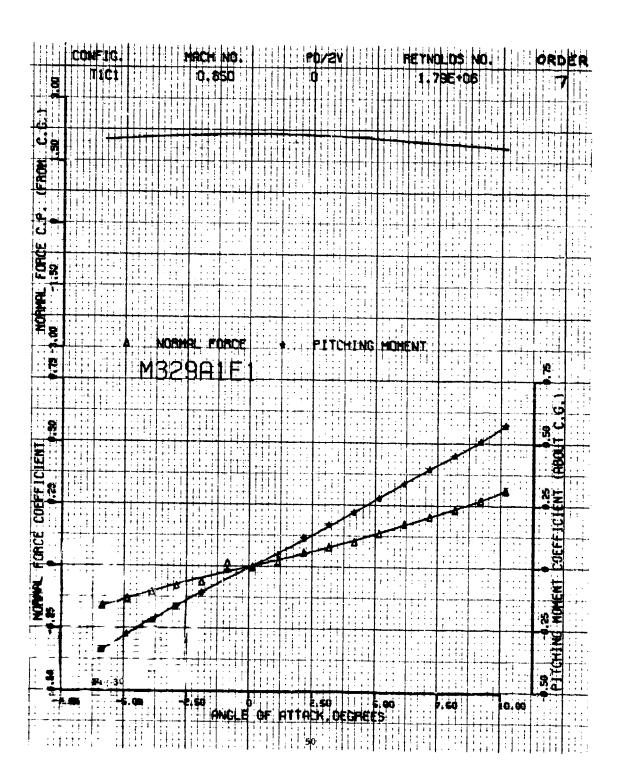


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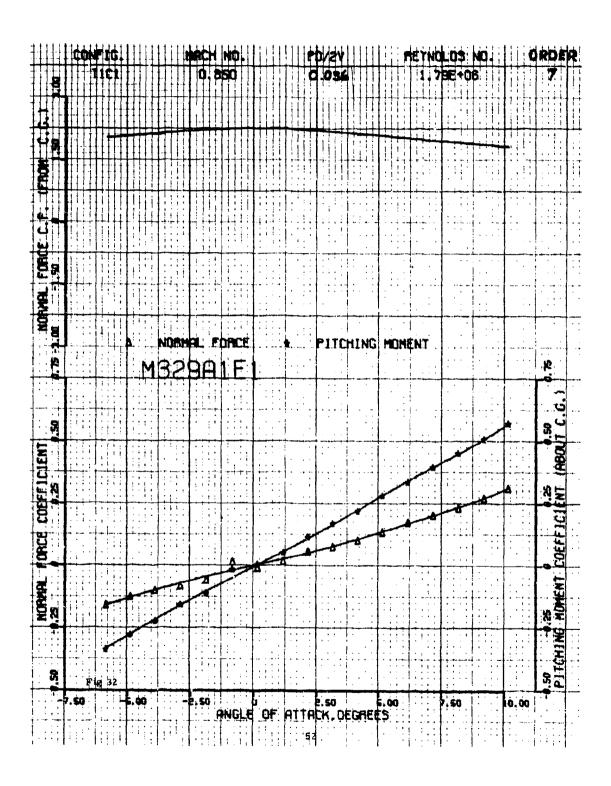


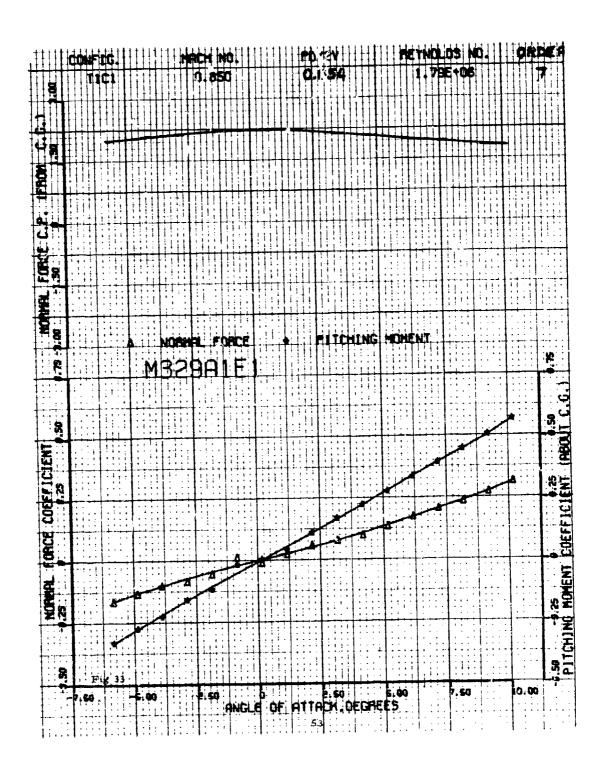


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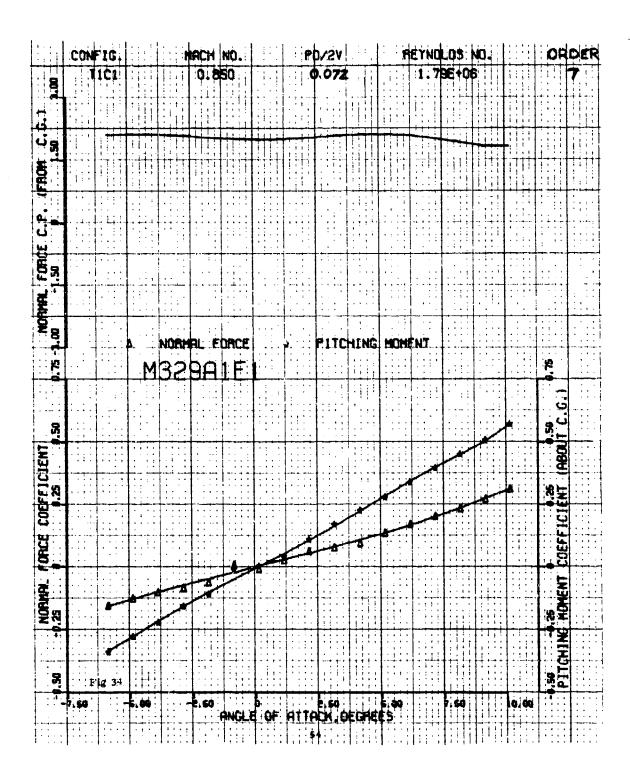


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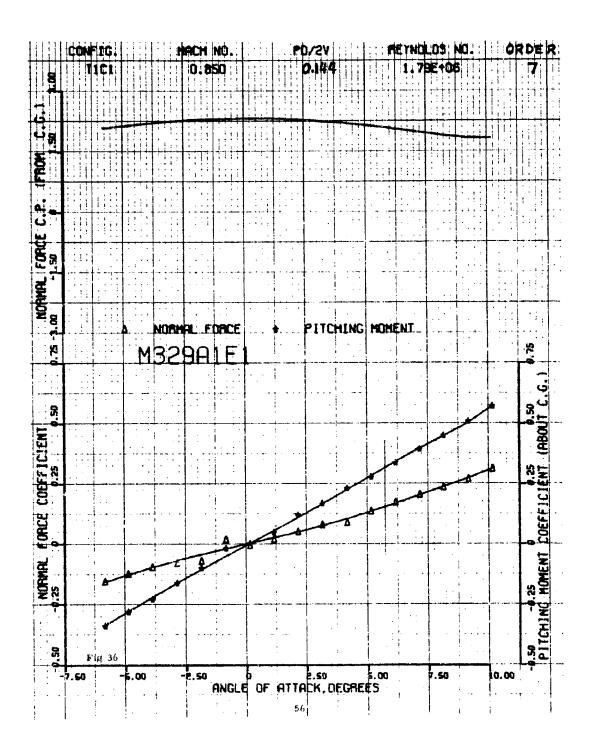


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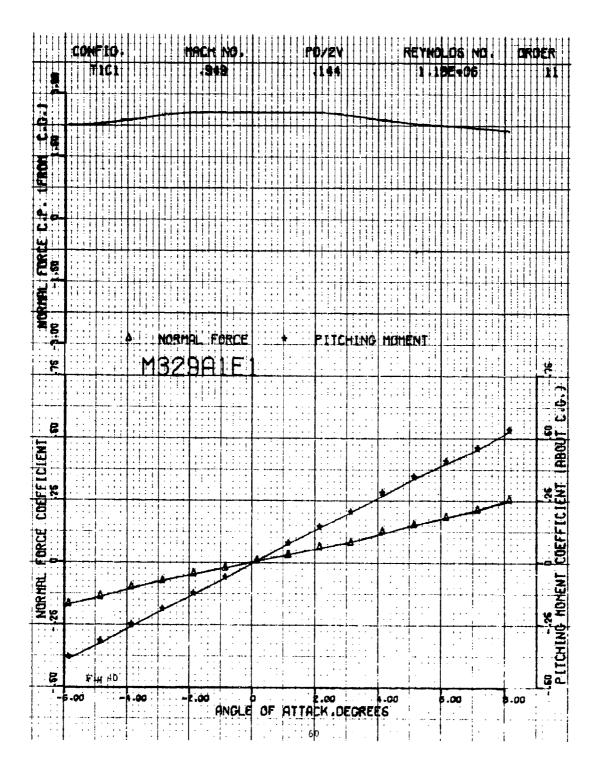


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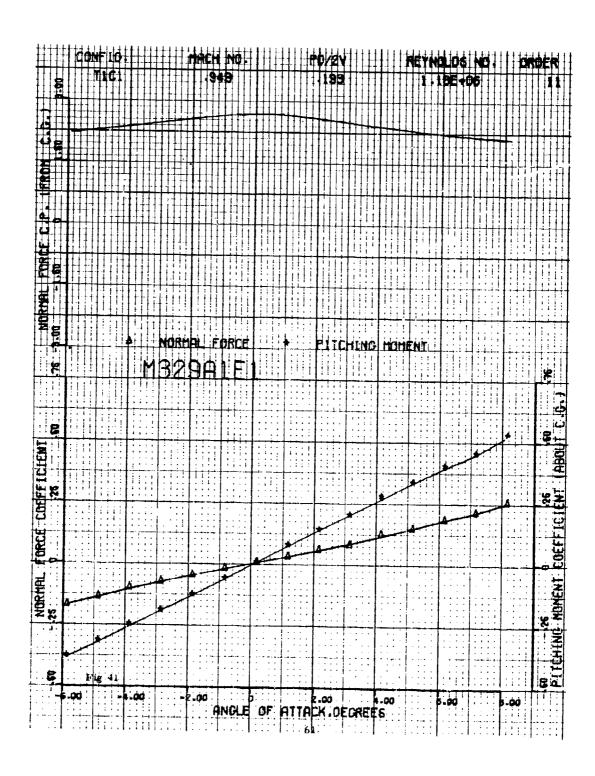
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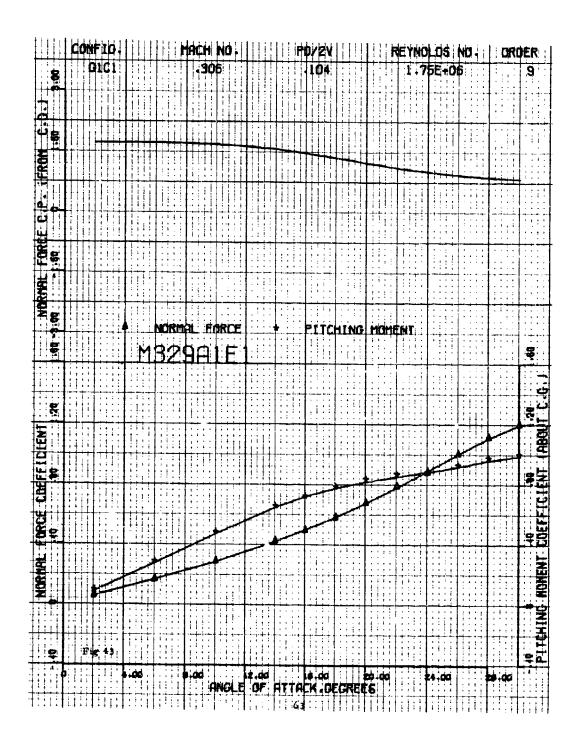


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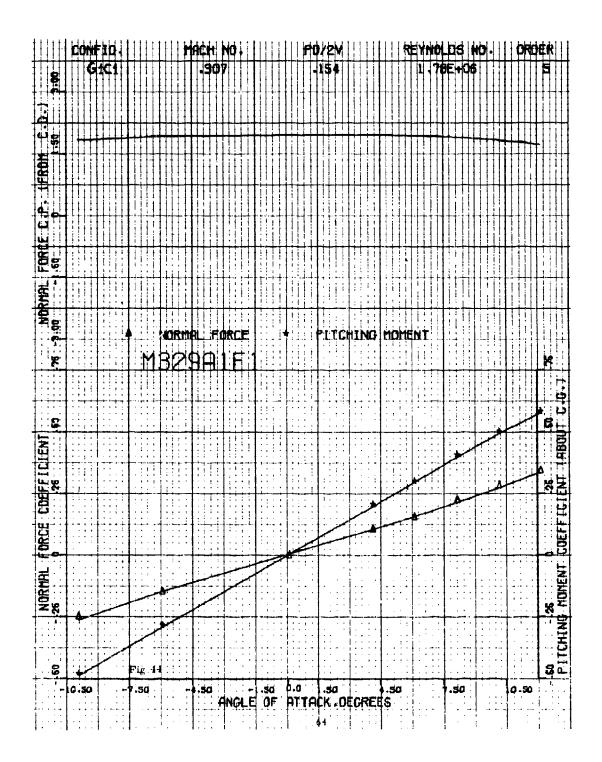


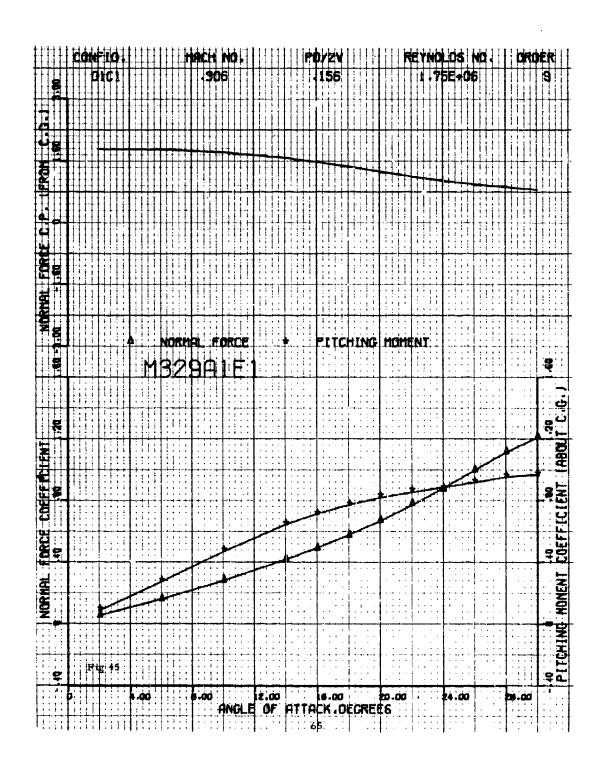
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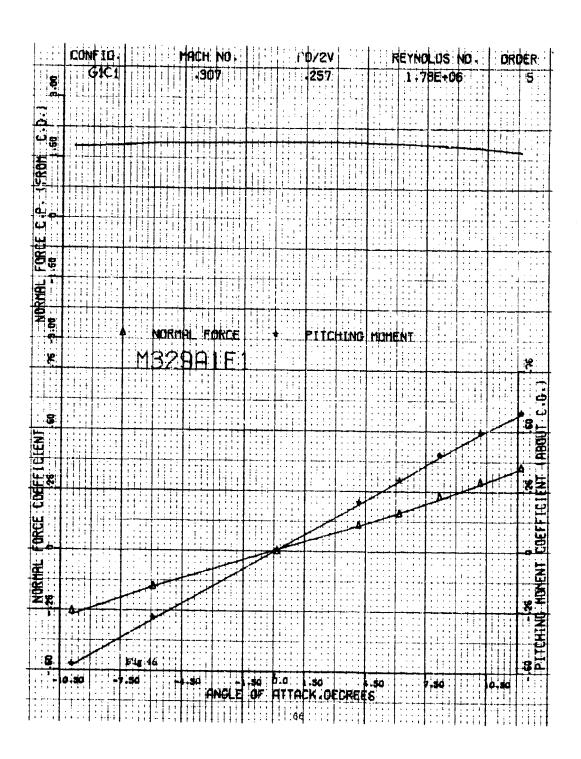
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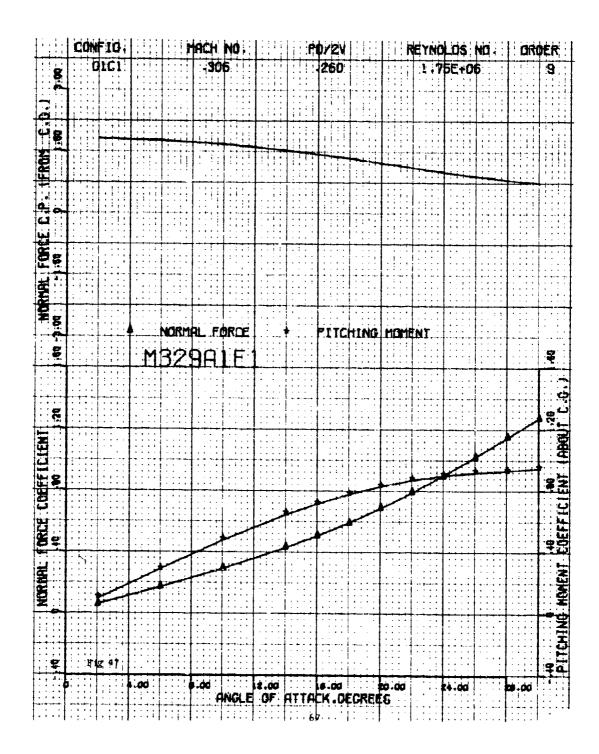
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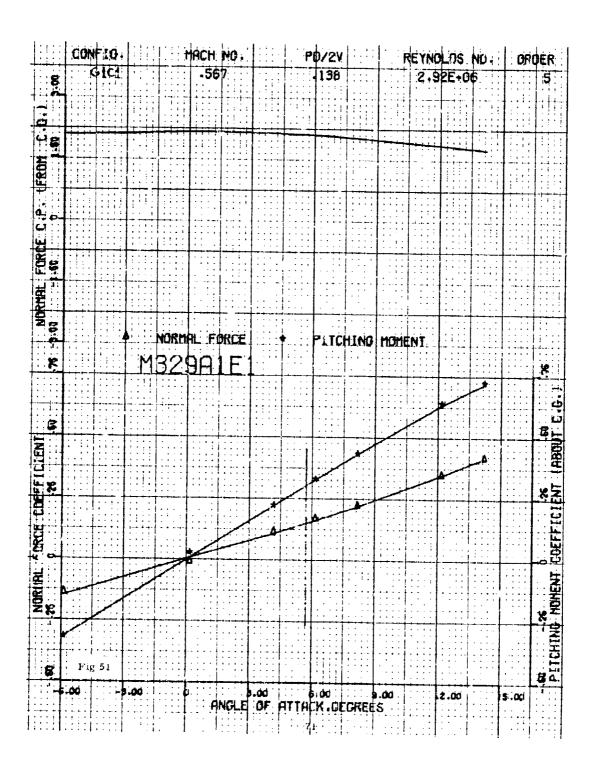
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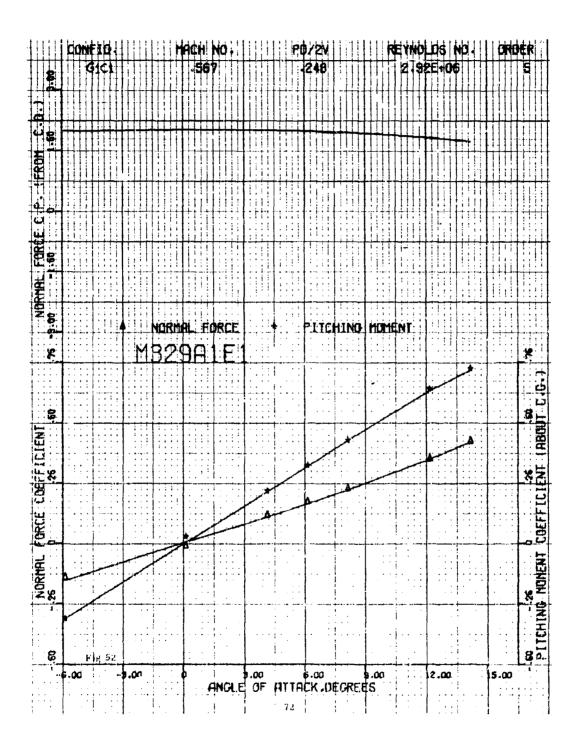
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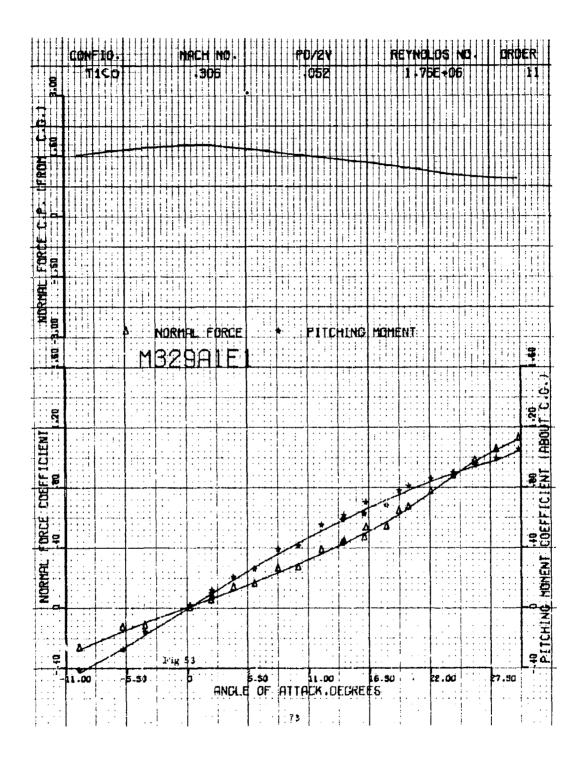
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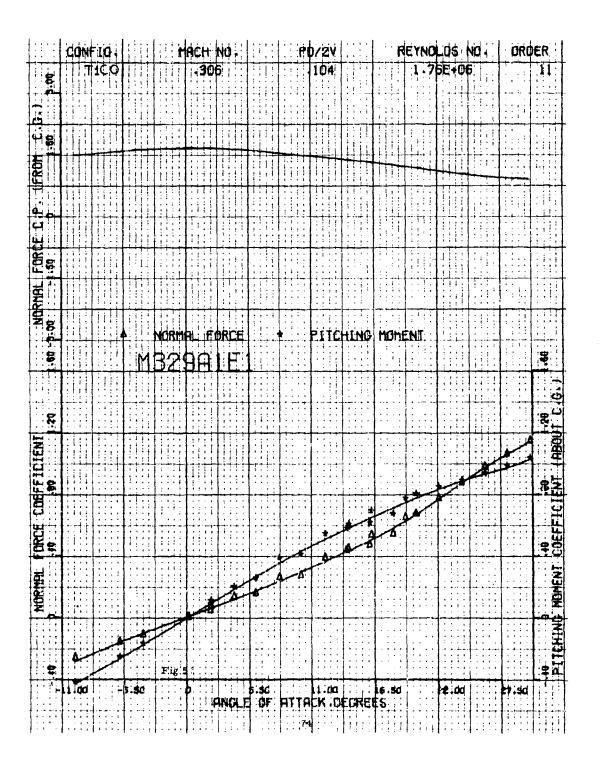


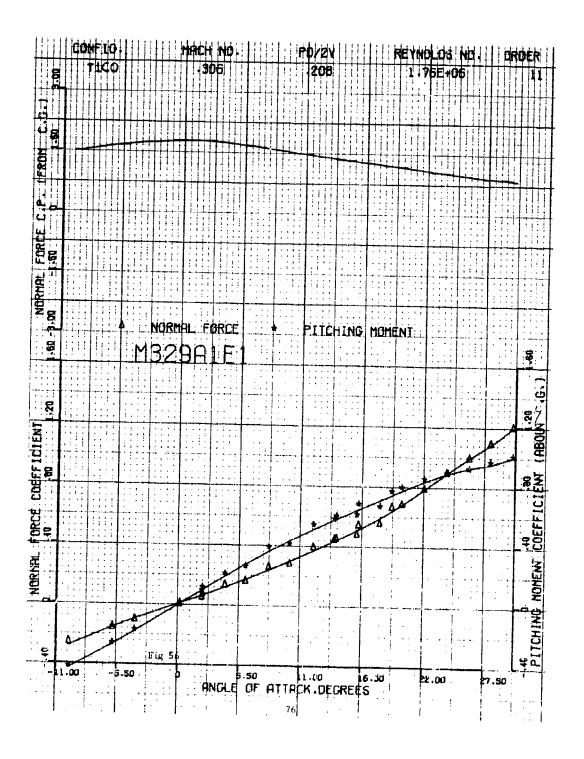


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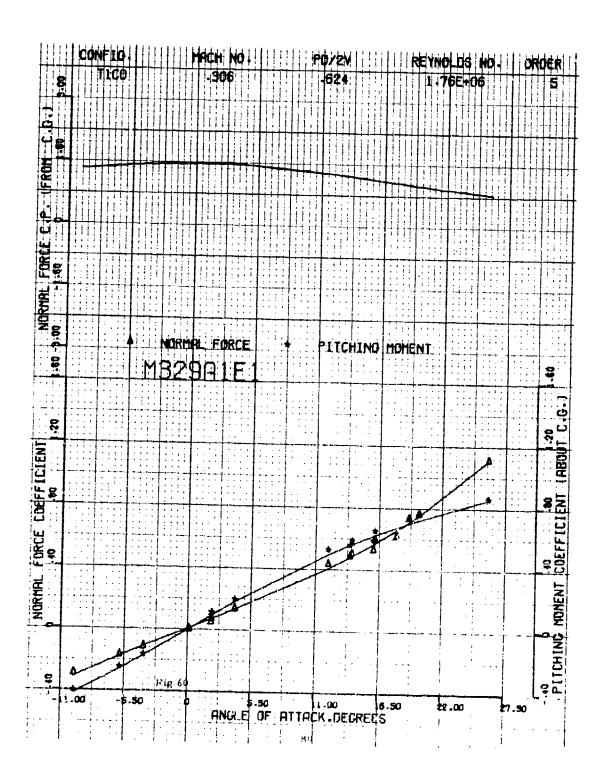




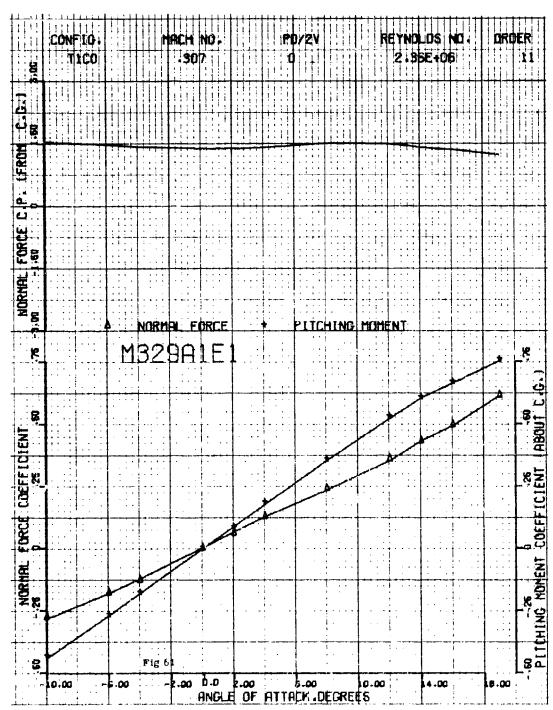
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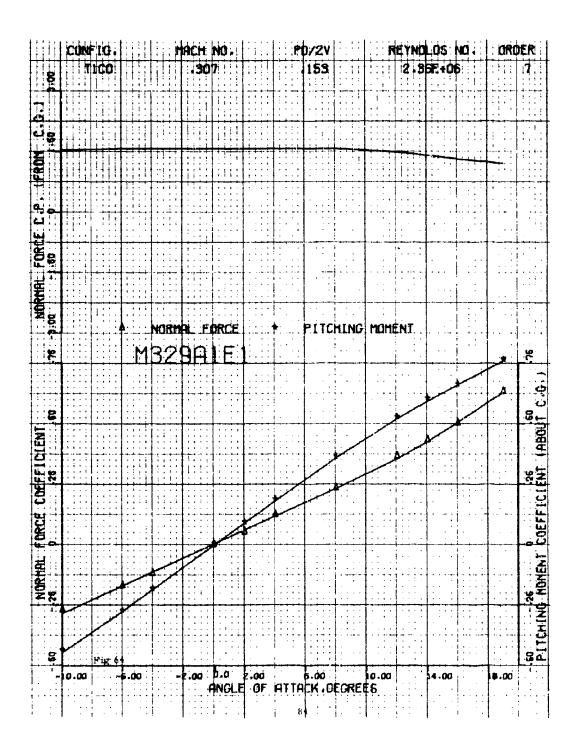


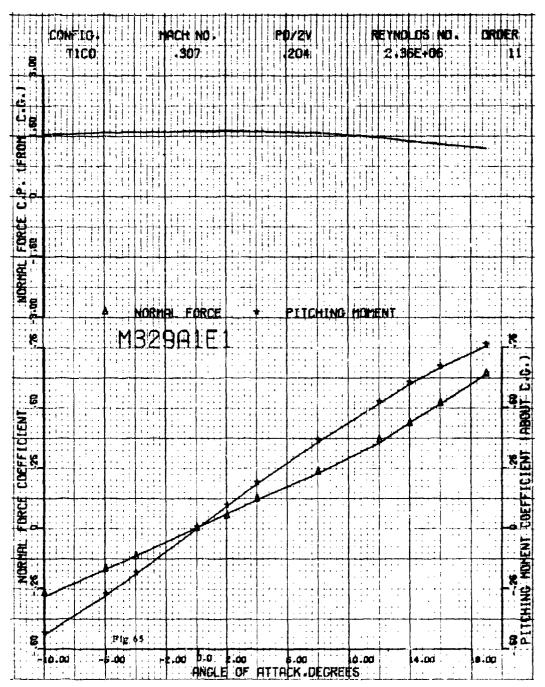
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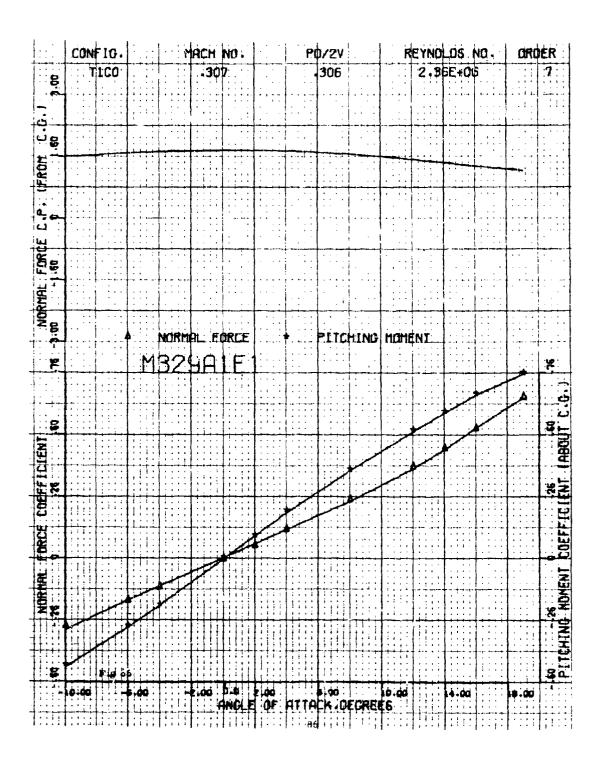


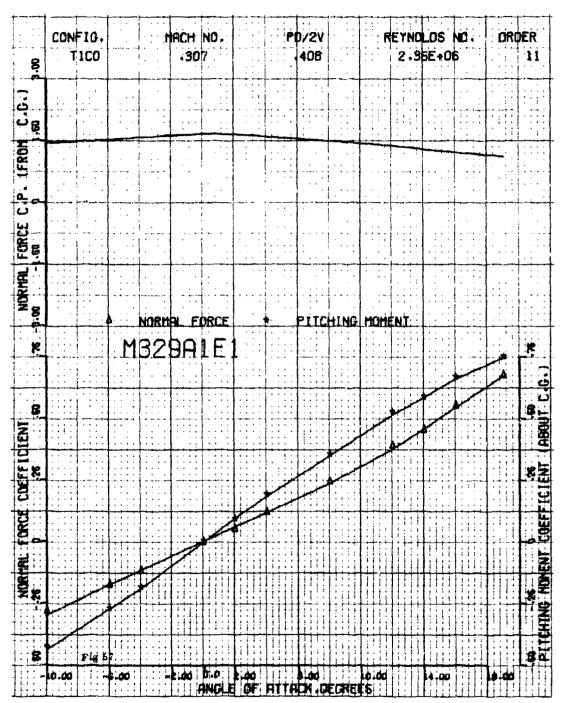
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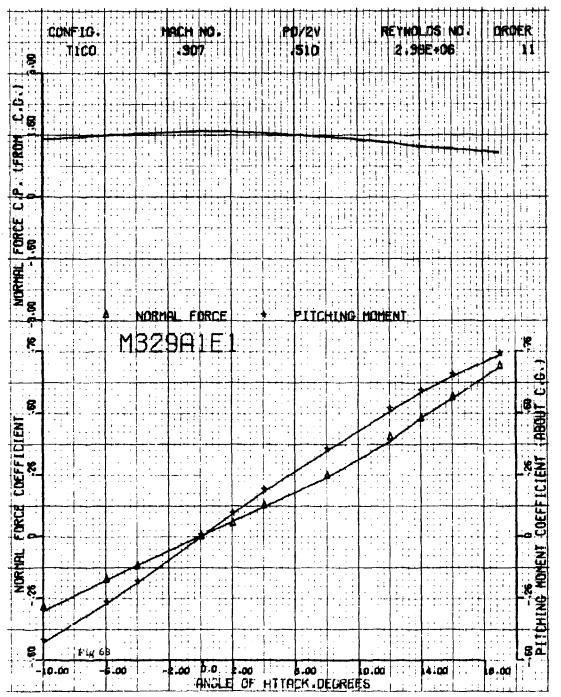
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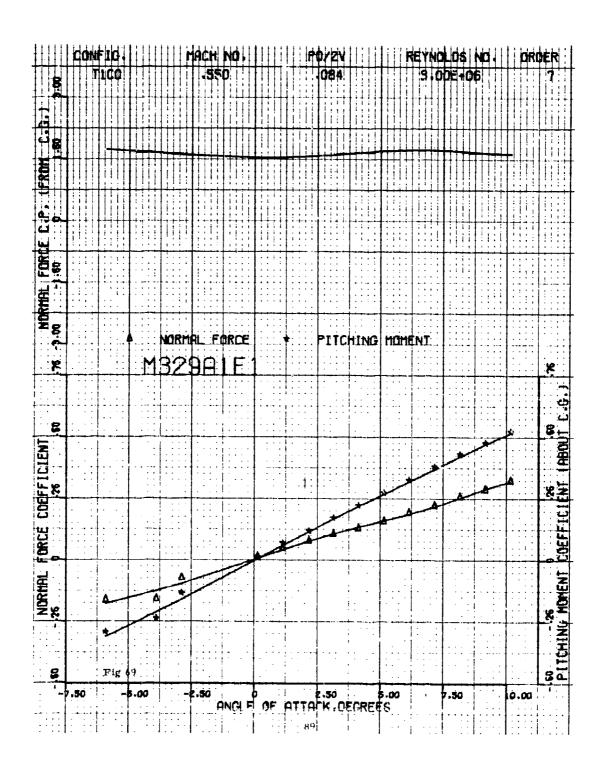


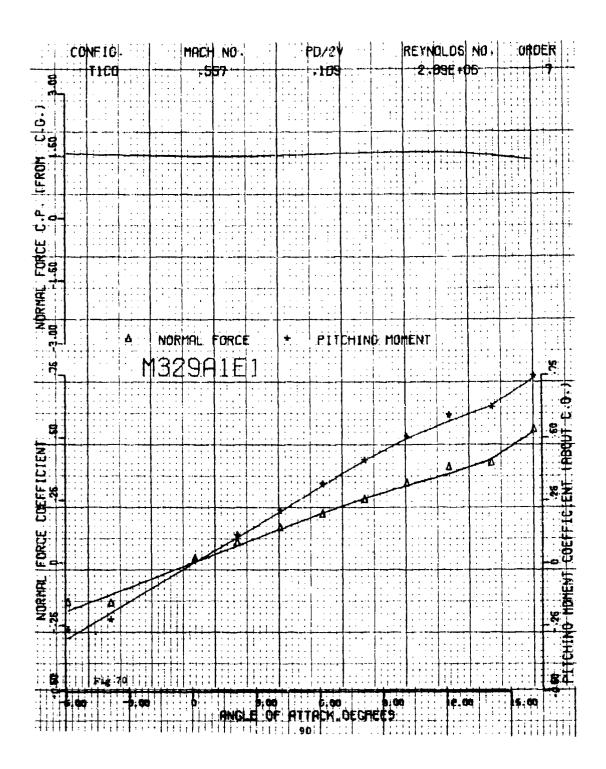






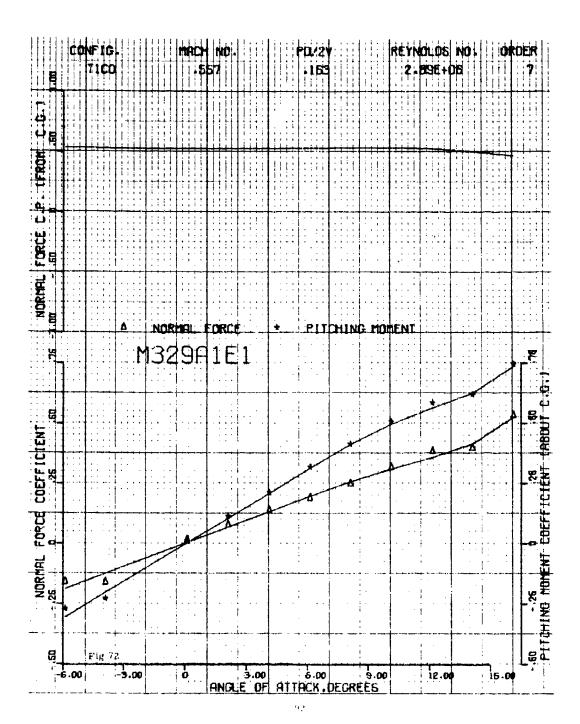






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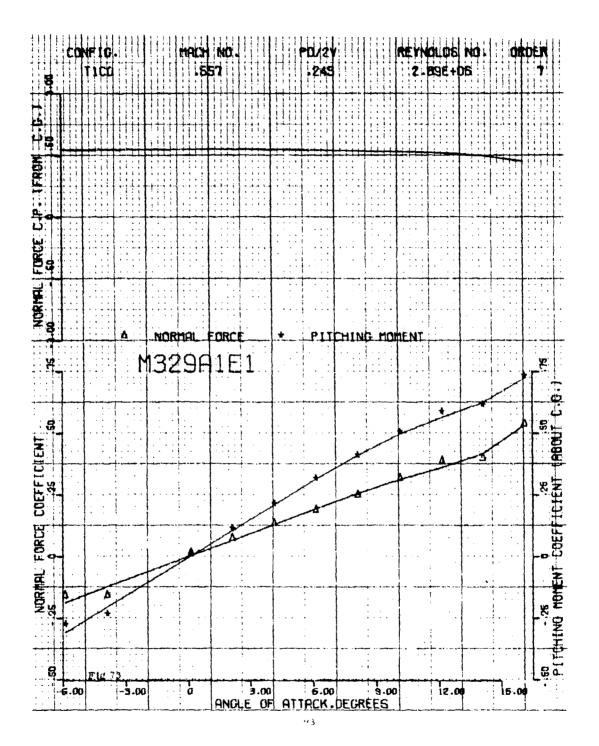


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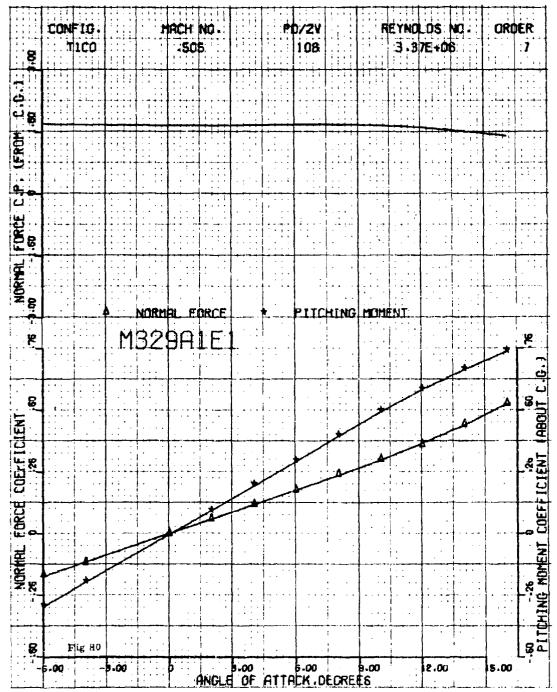
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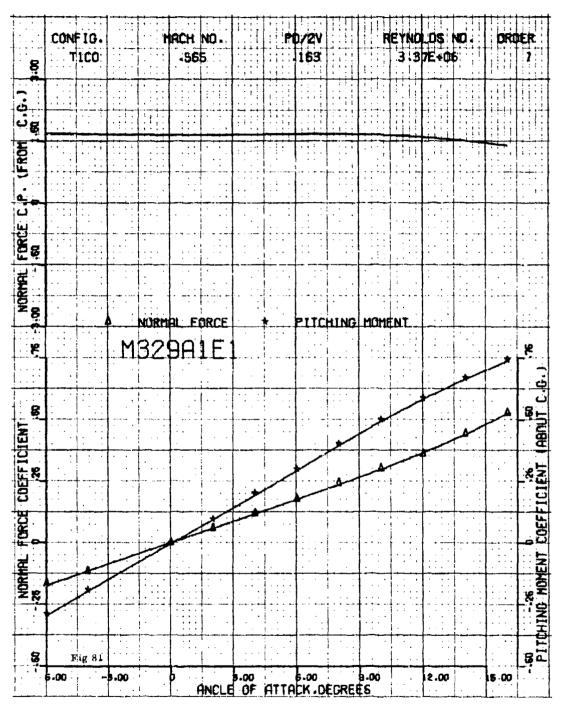
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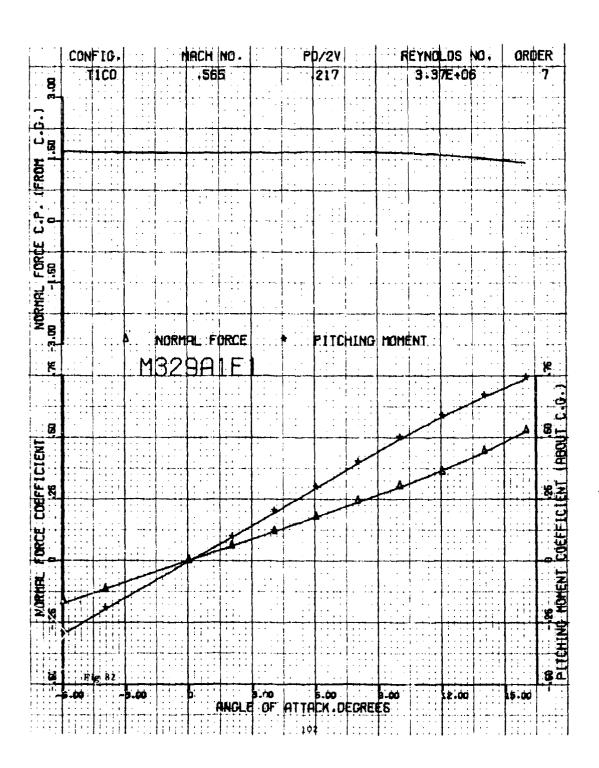
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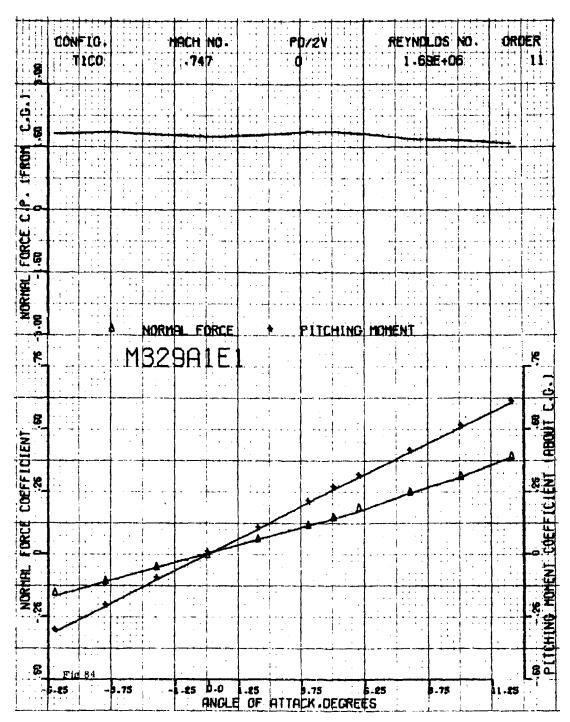


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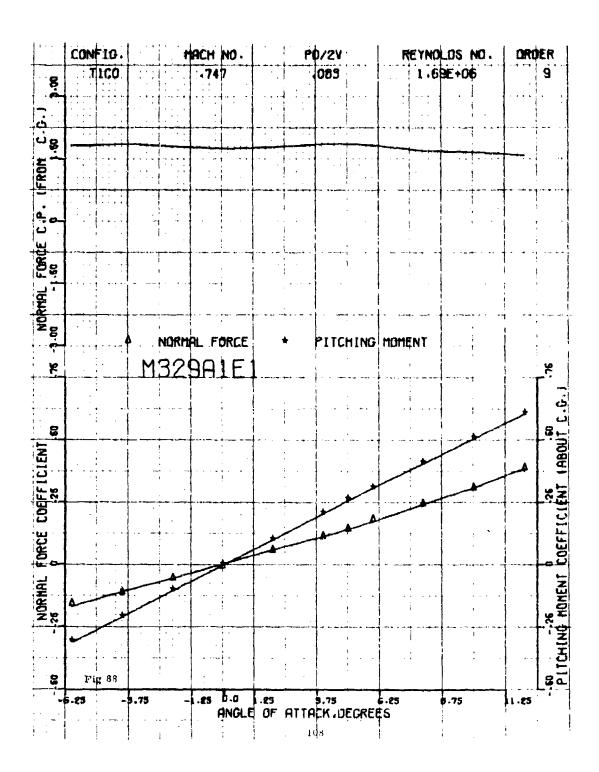
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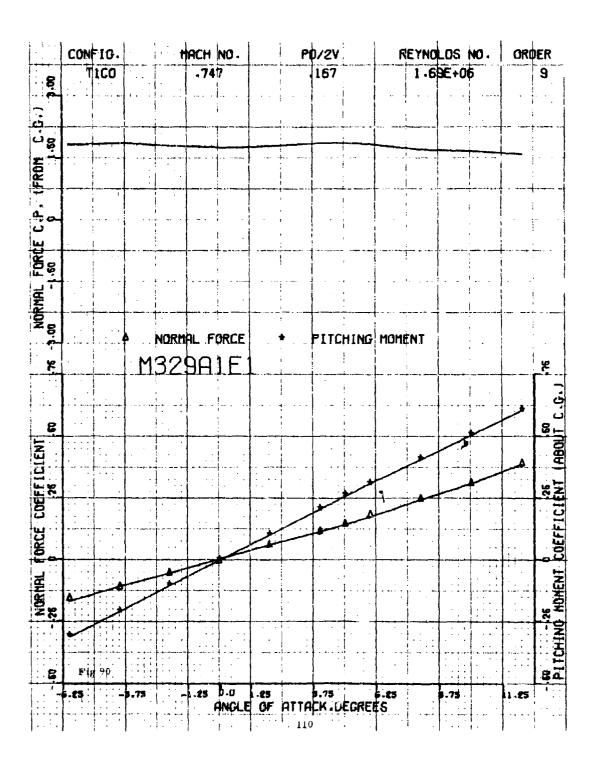
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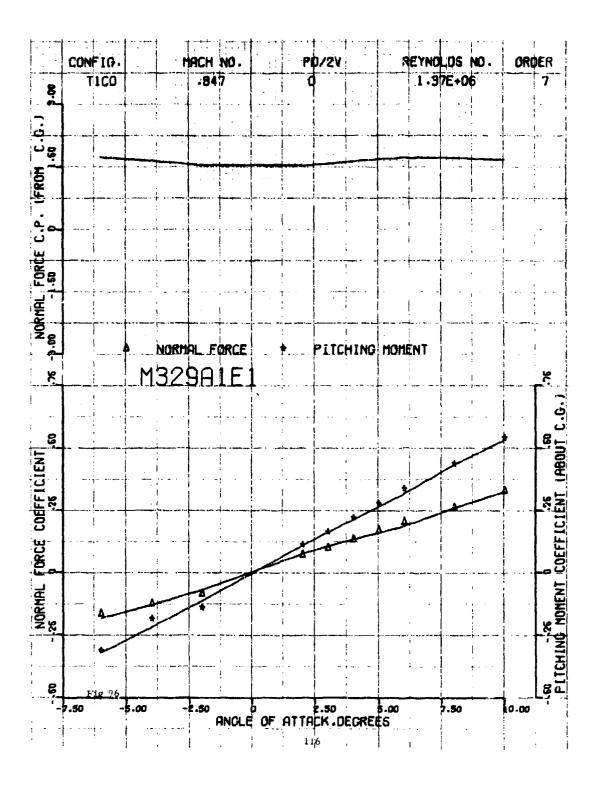
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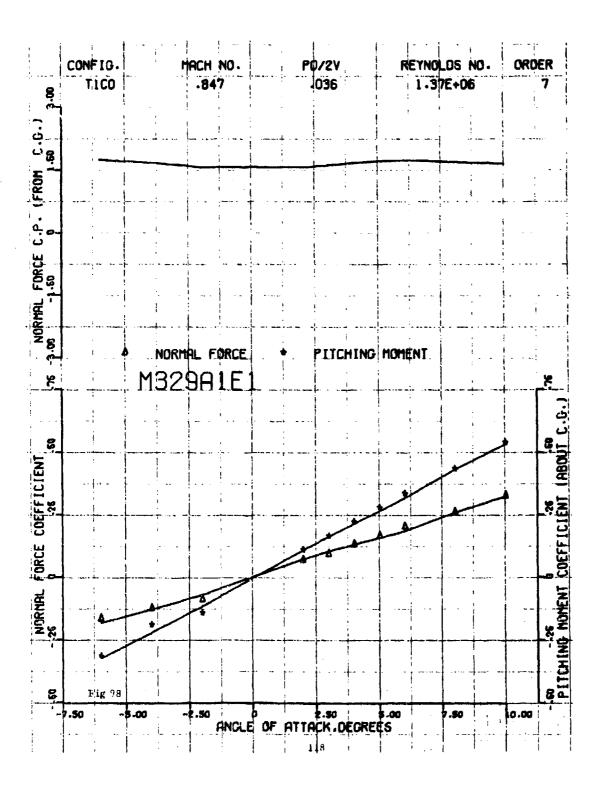
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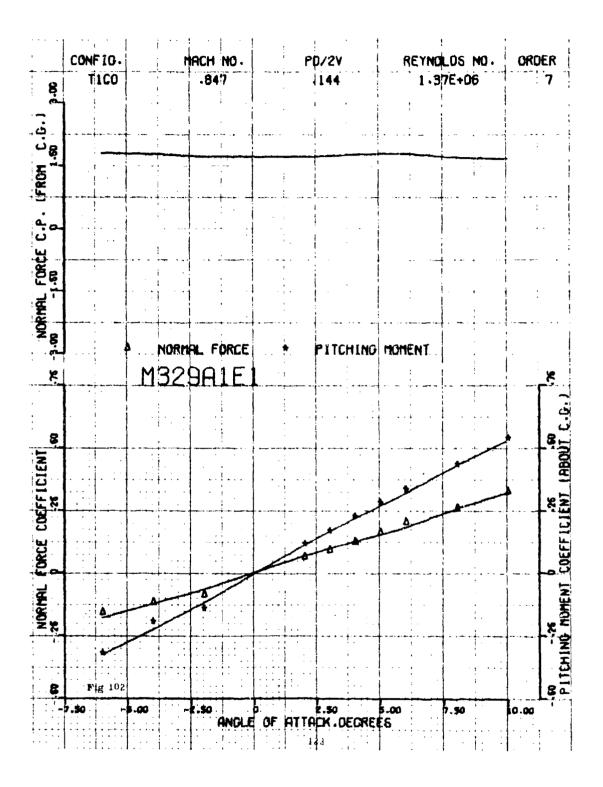


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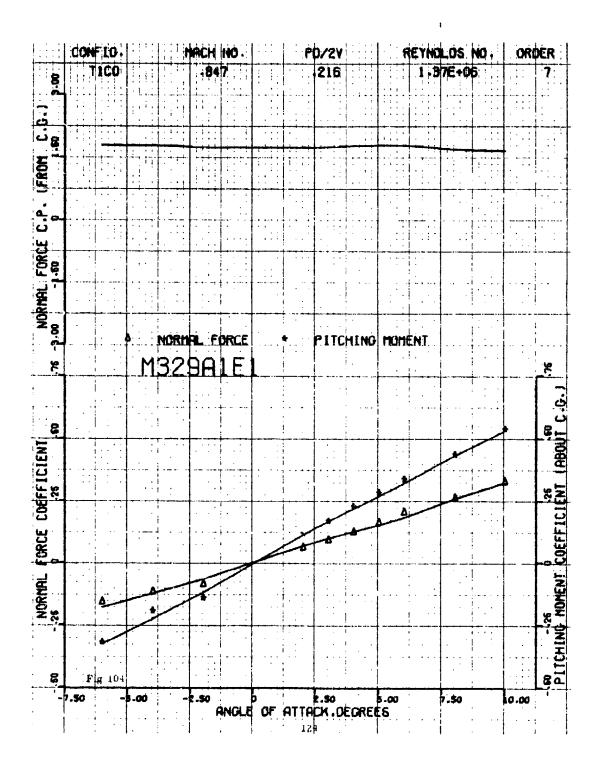


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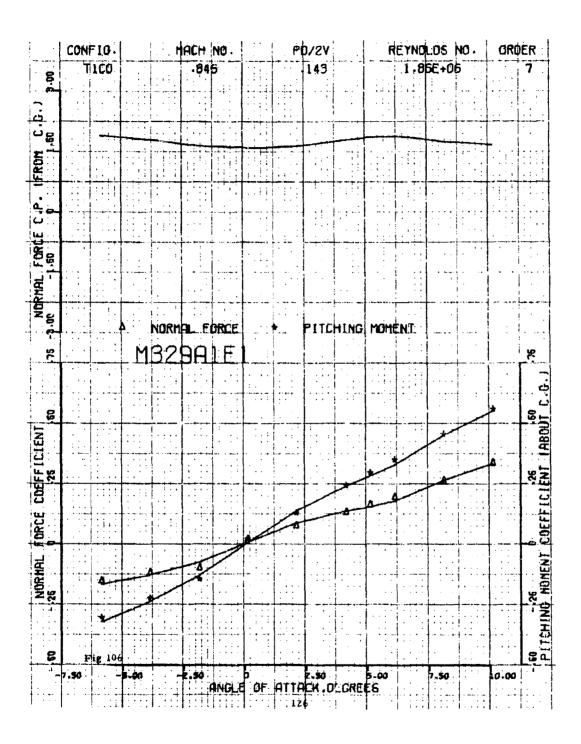
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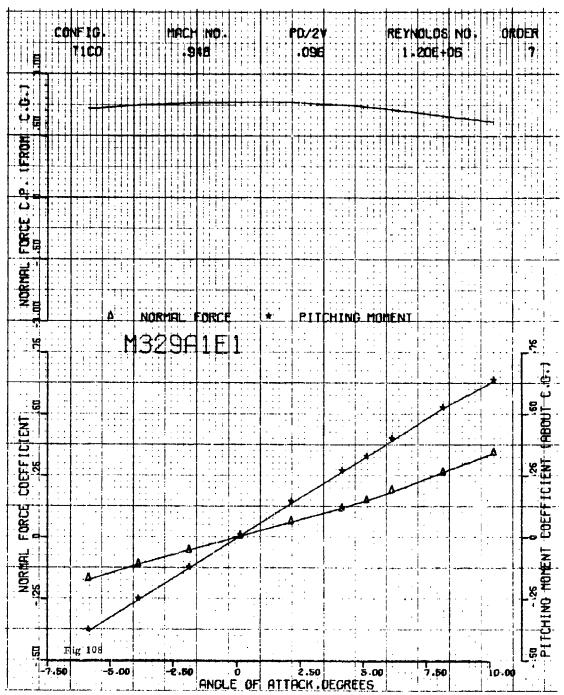
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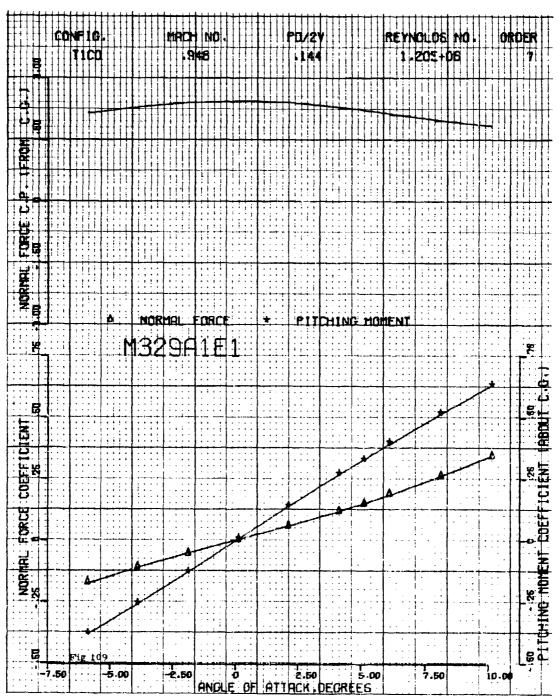
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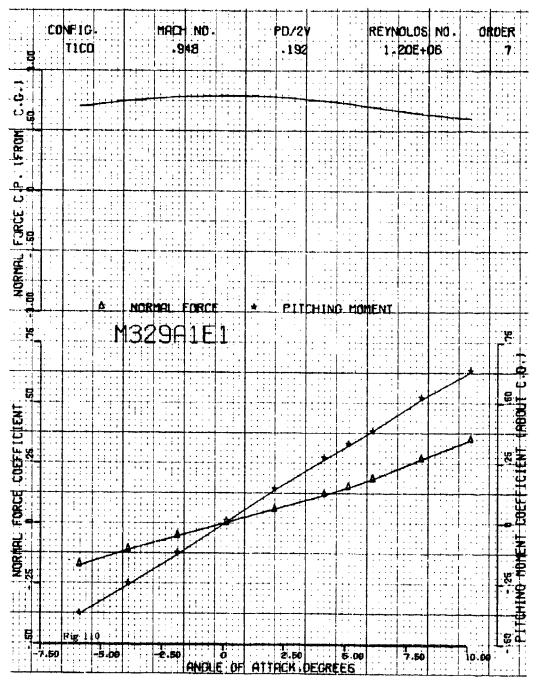
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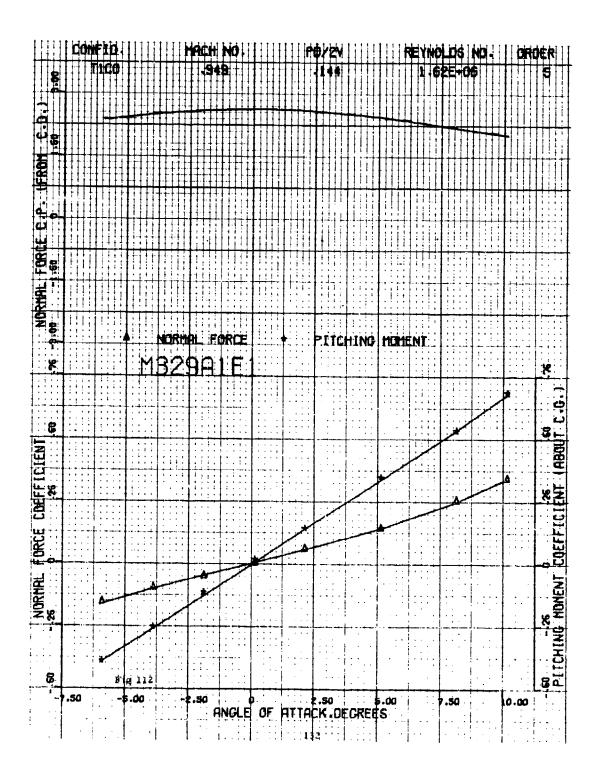


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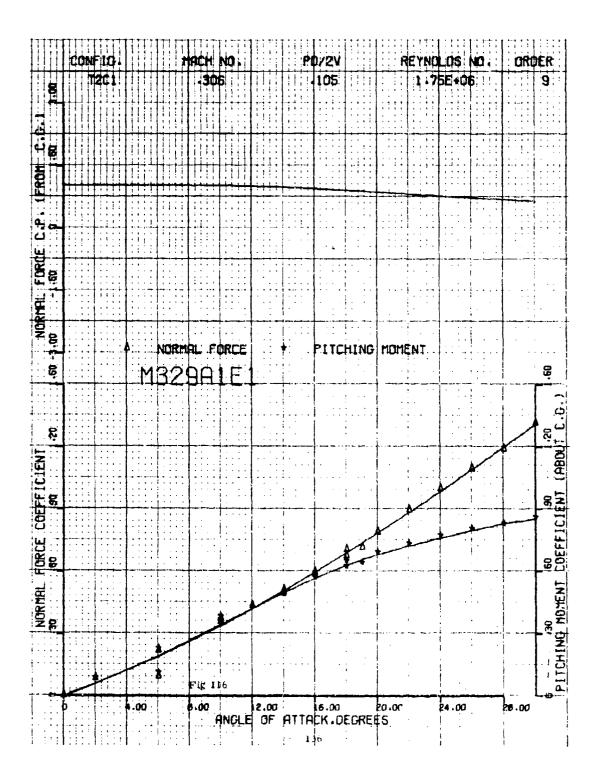
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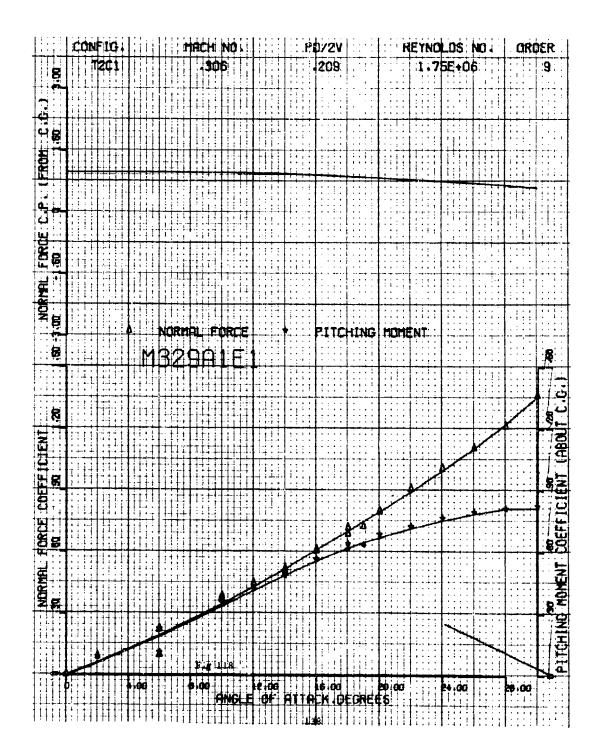
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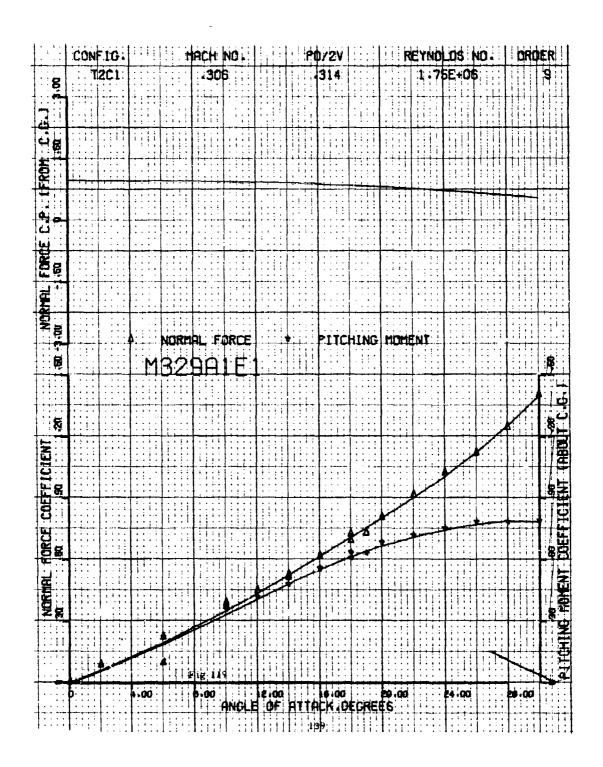
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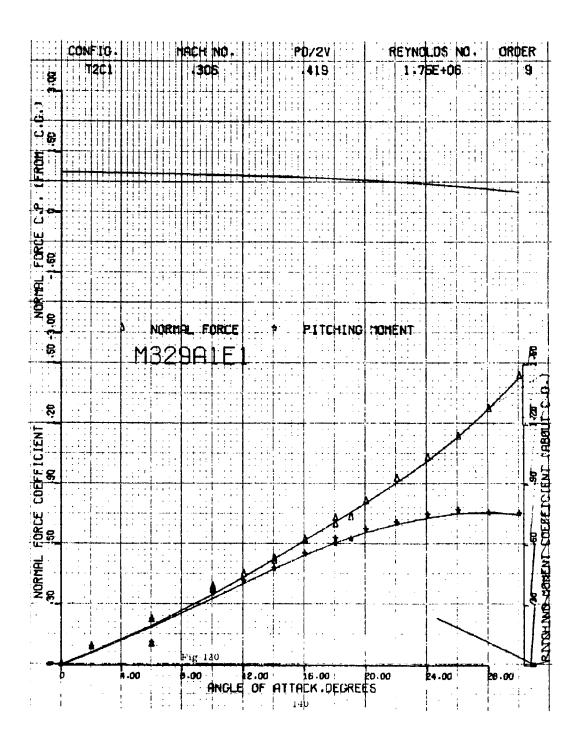


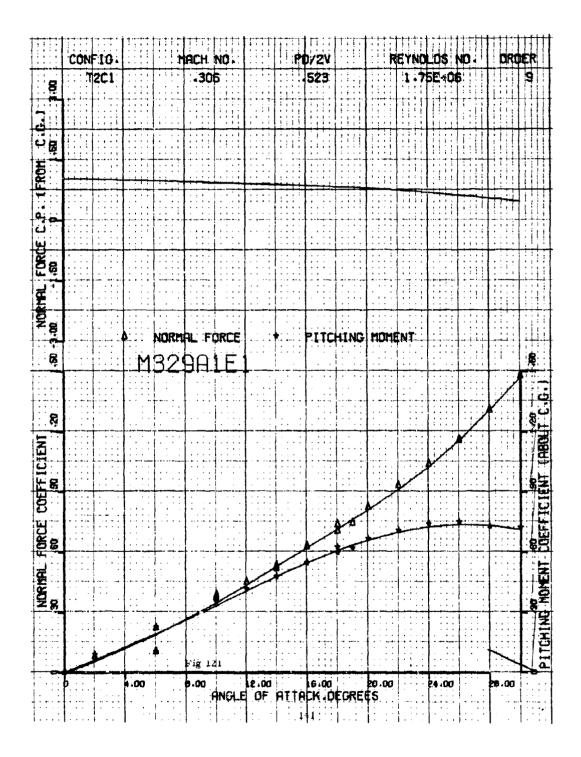
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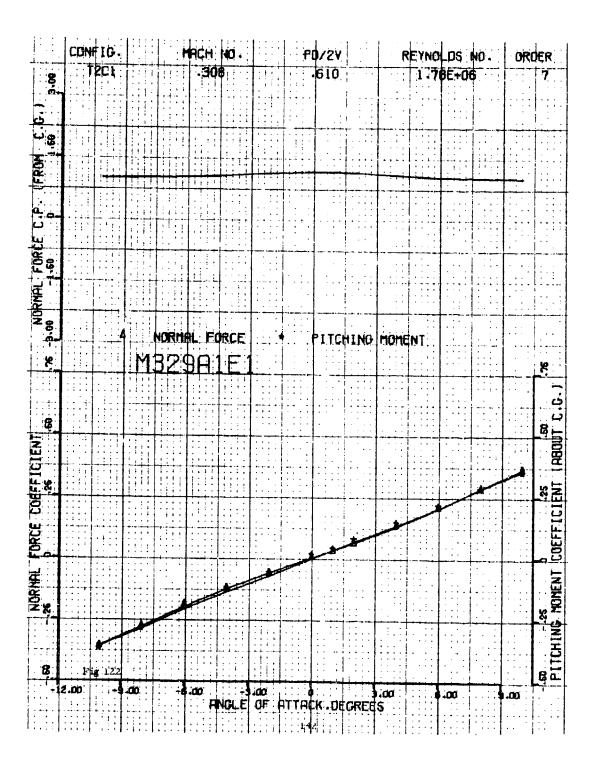
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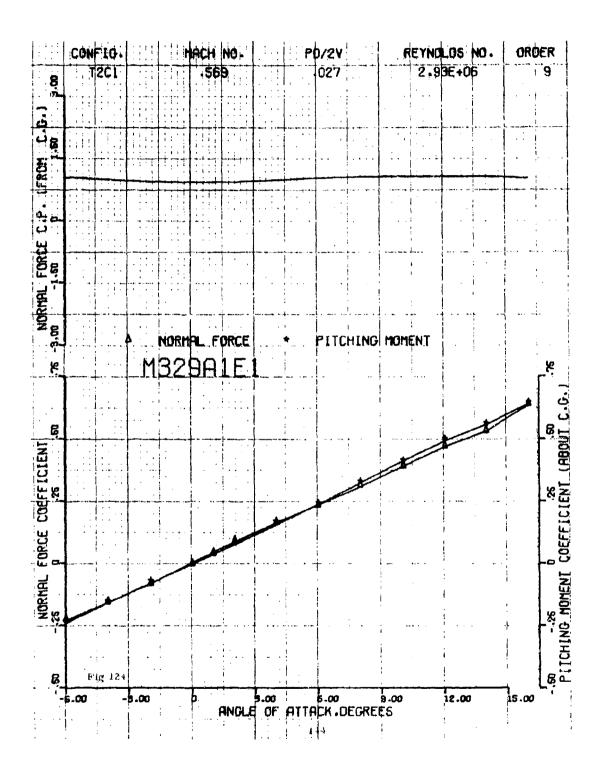




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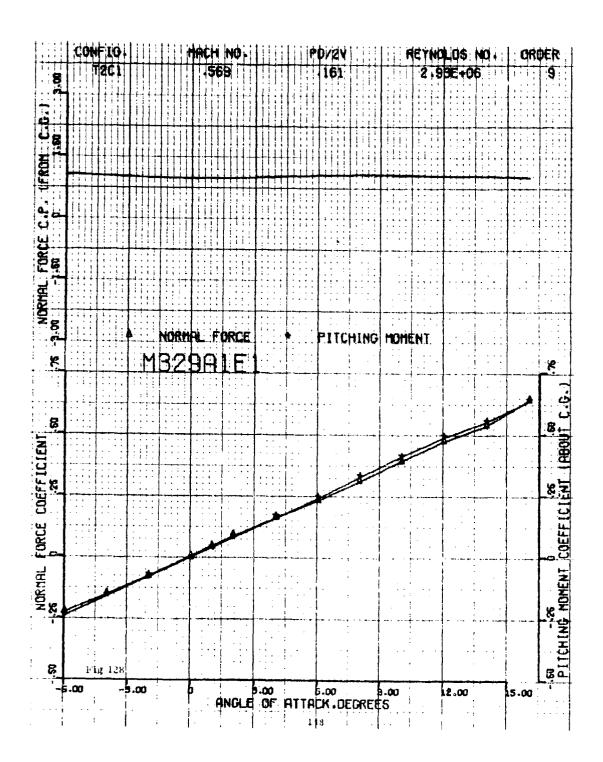


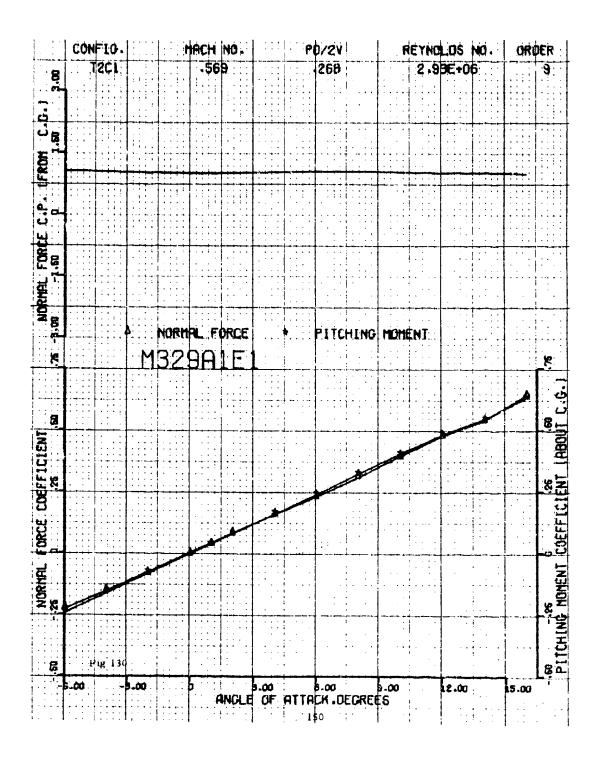
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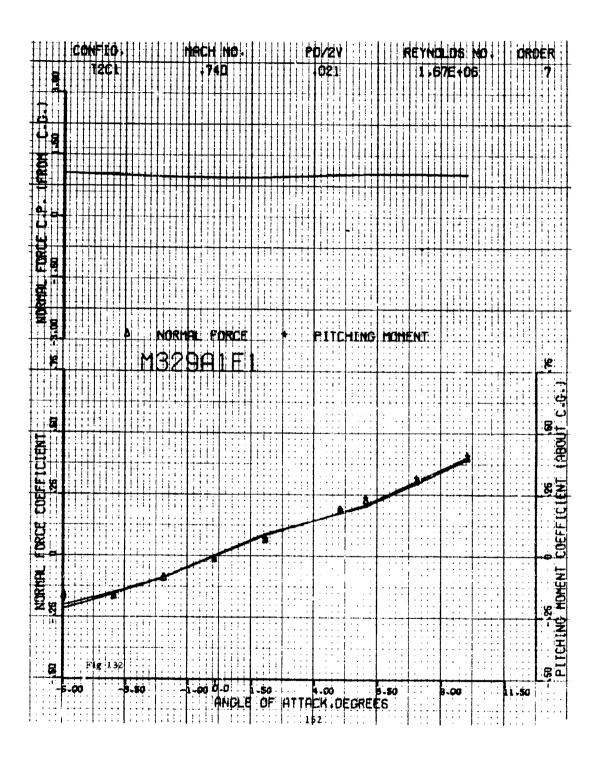


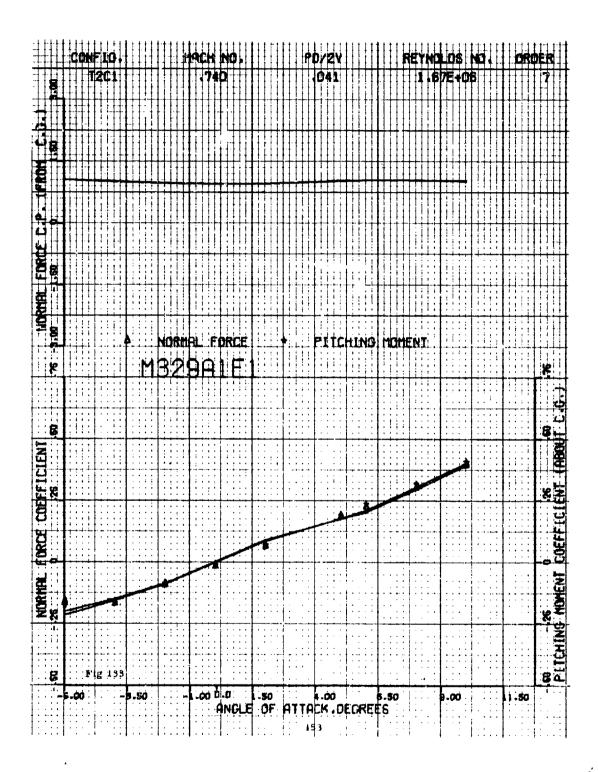


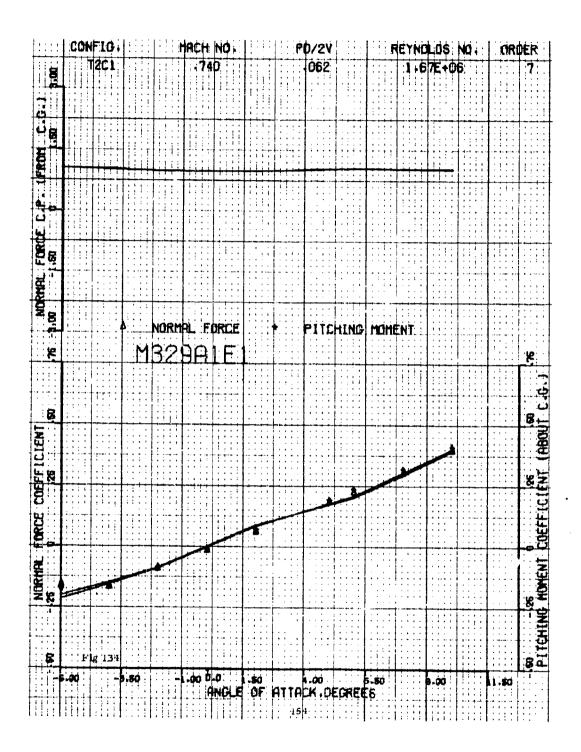
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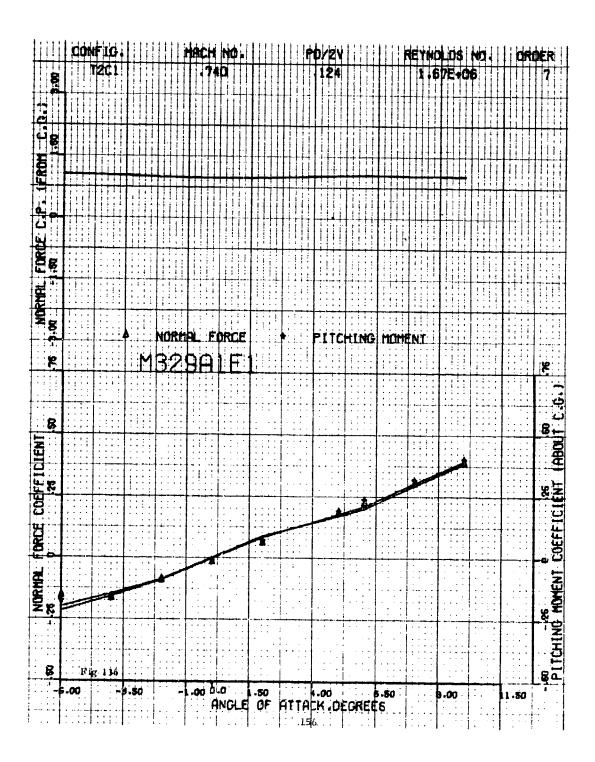
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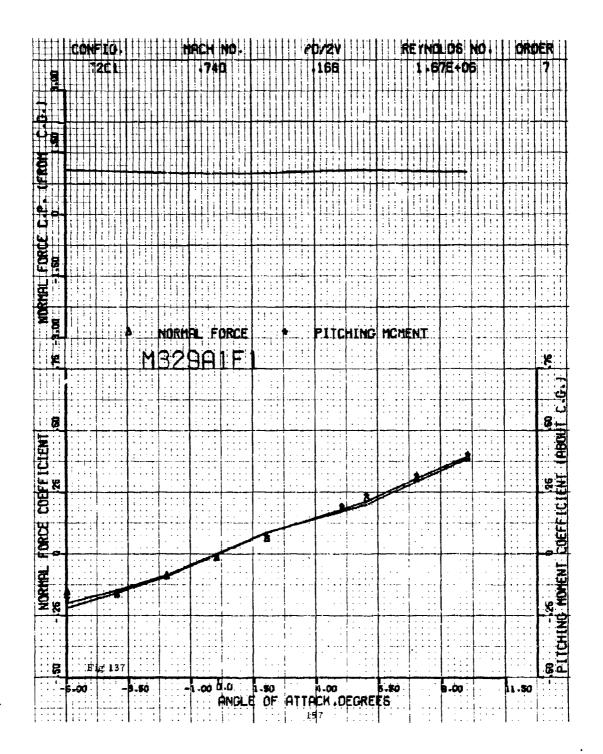






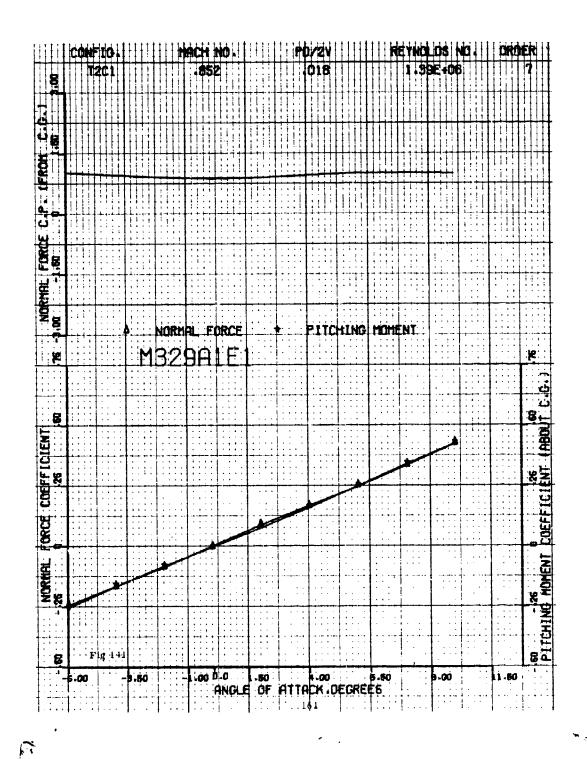
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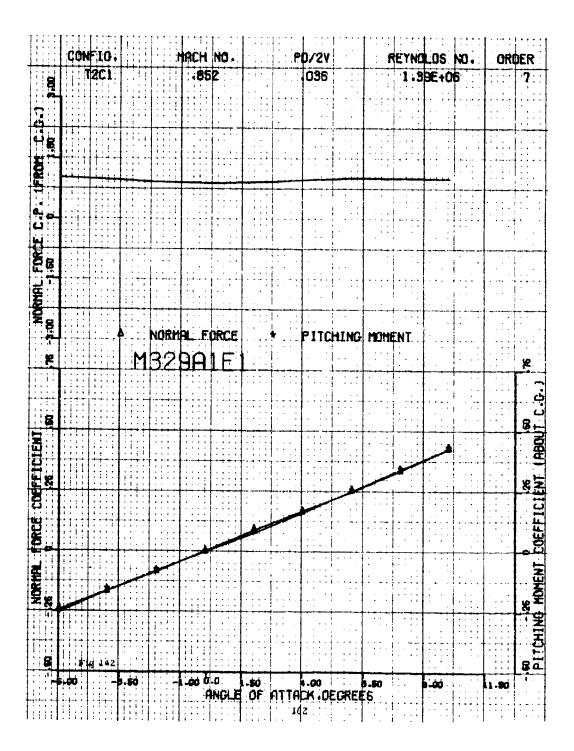




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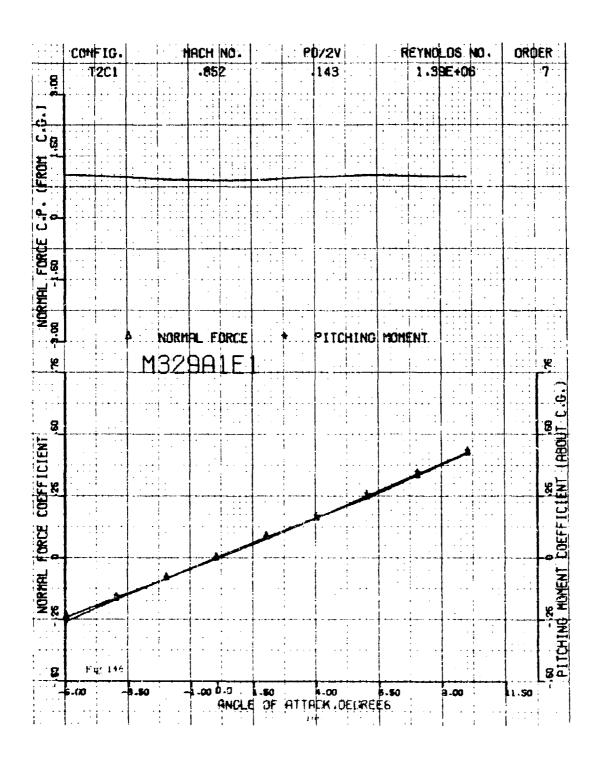
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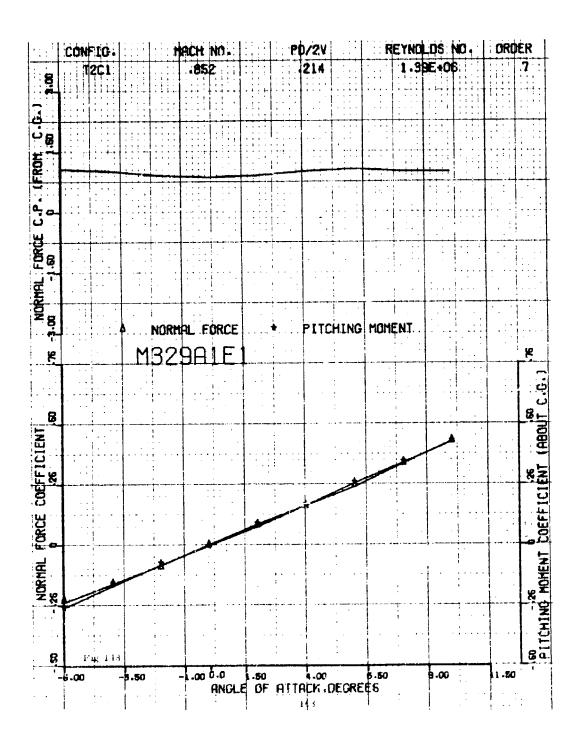
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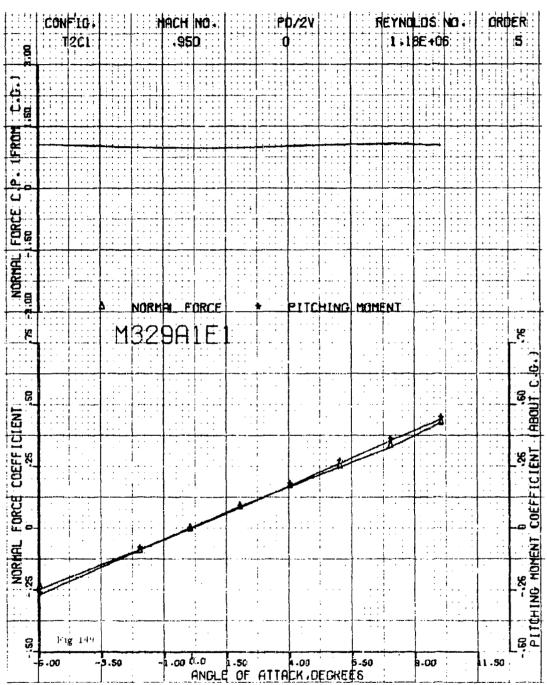
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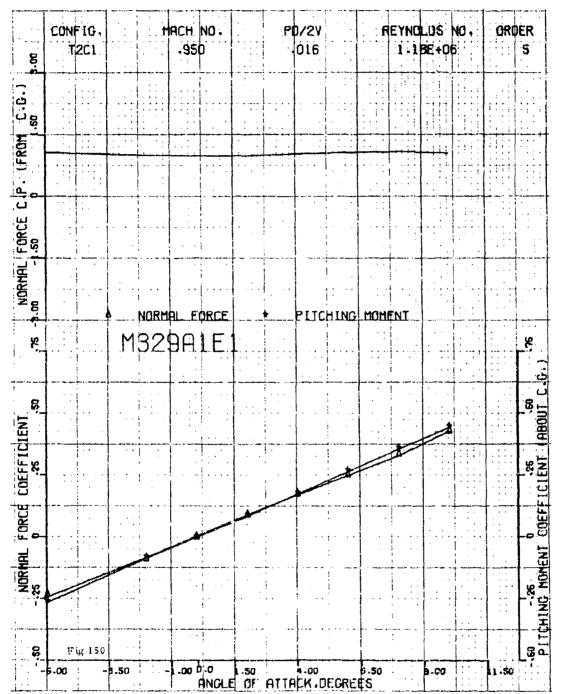


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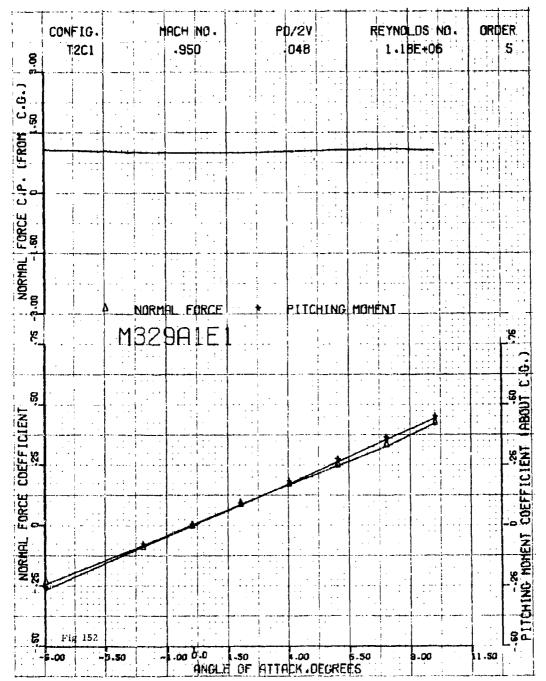




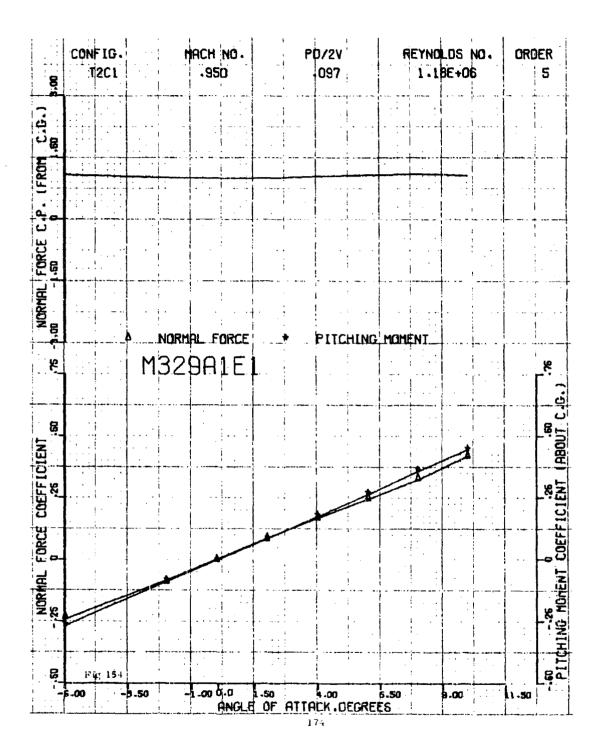
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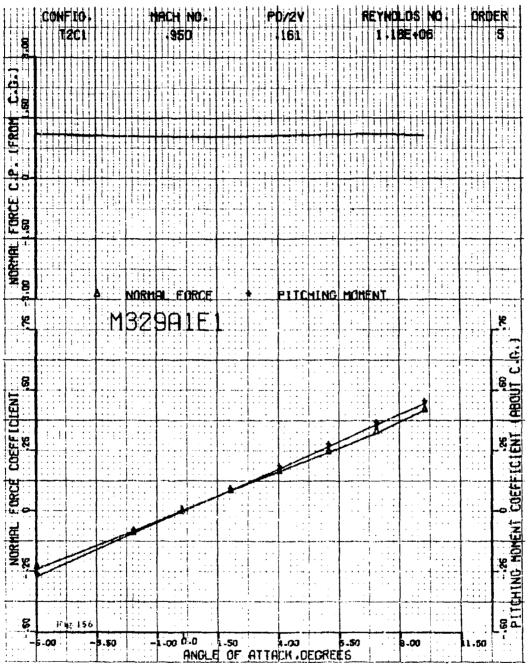
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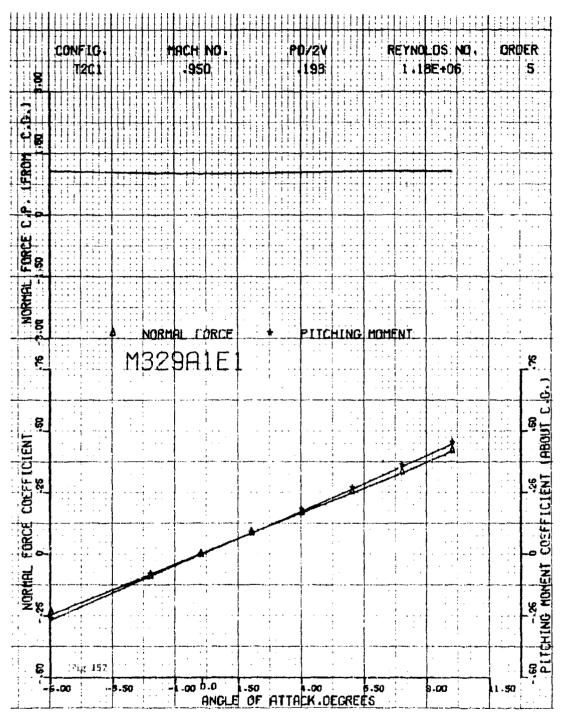


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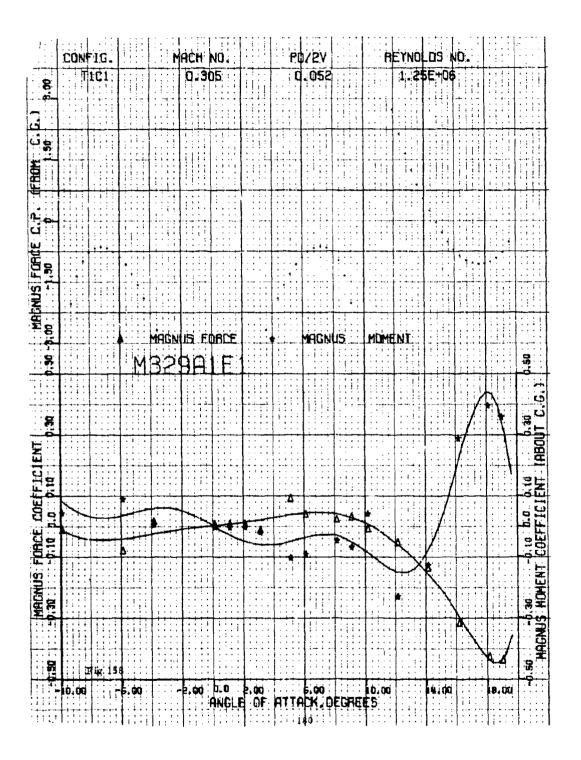


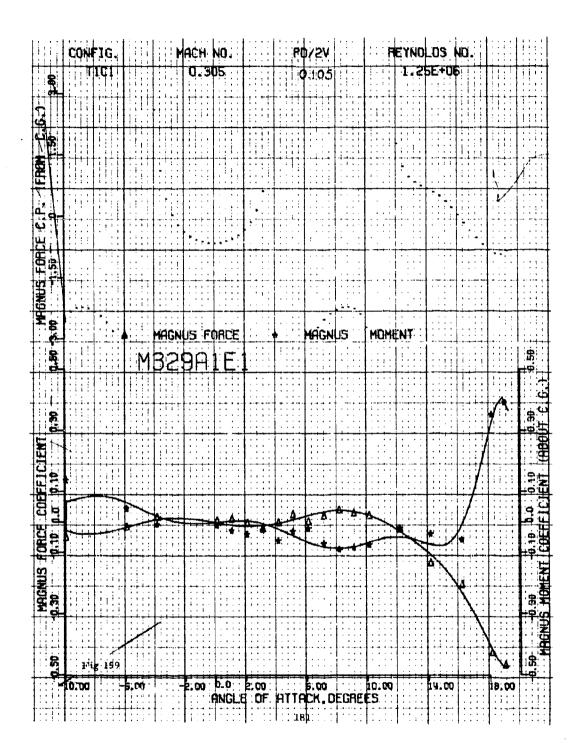
Figures 158 through 333

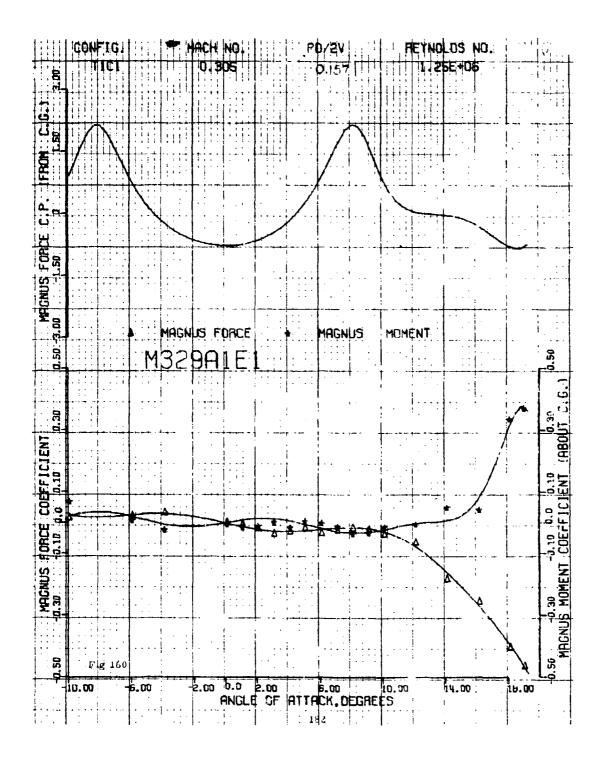
Magnus force coefficient, Magnus moment coefficient, Magnus force center of pressure vs angle of attack.

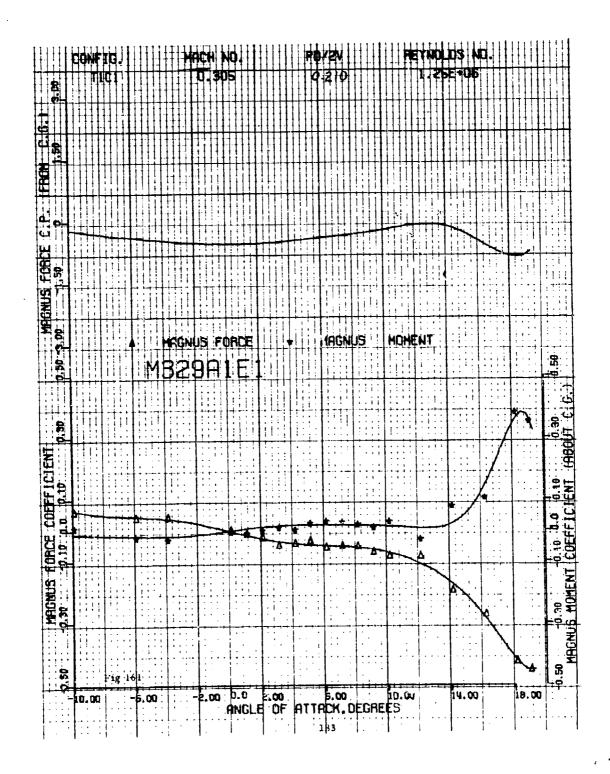
(Includes several configurations, Mach numbers, pd/2V's and Reynolds numbers [12' PWT].)

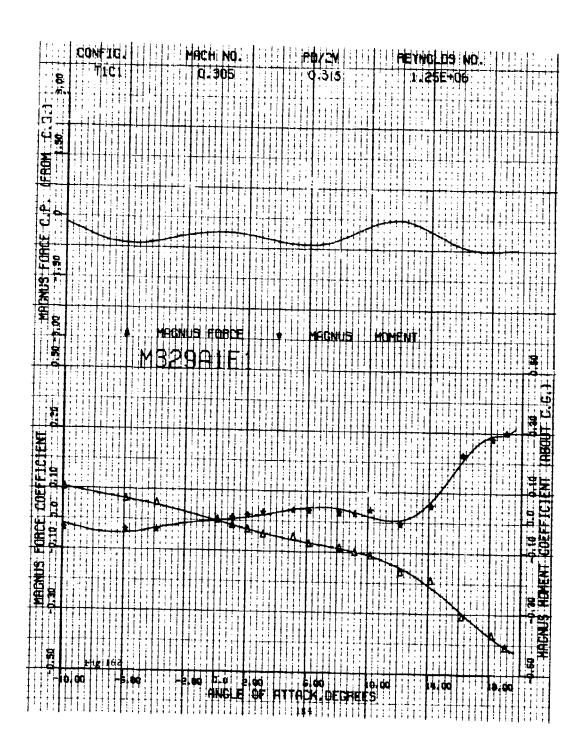
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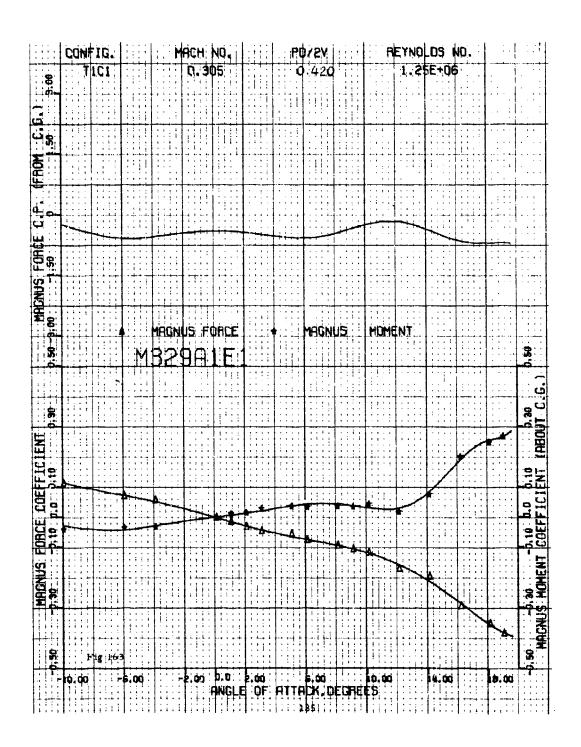


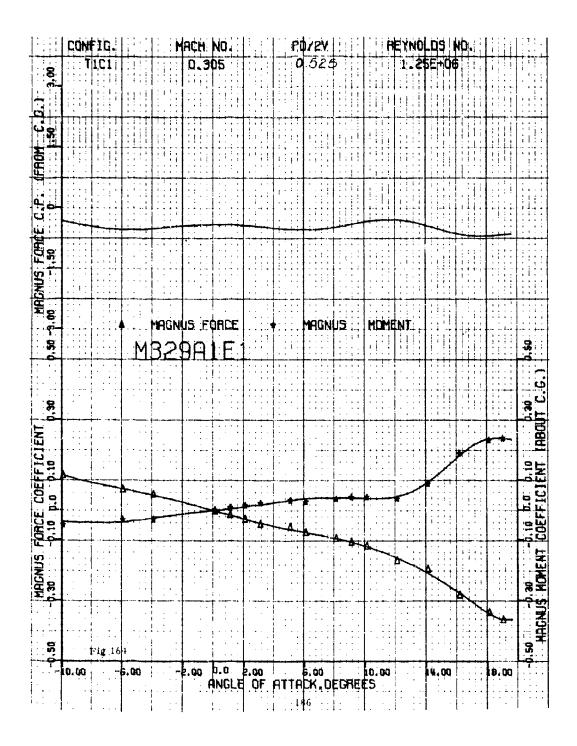


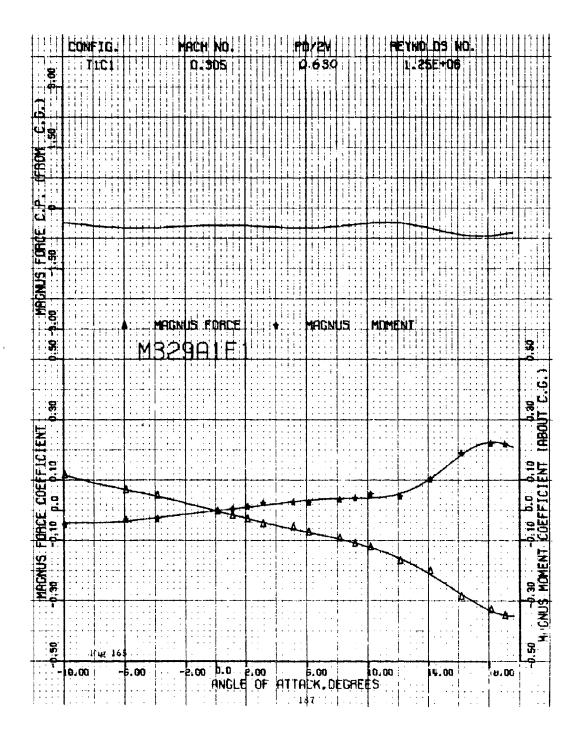


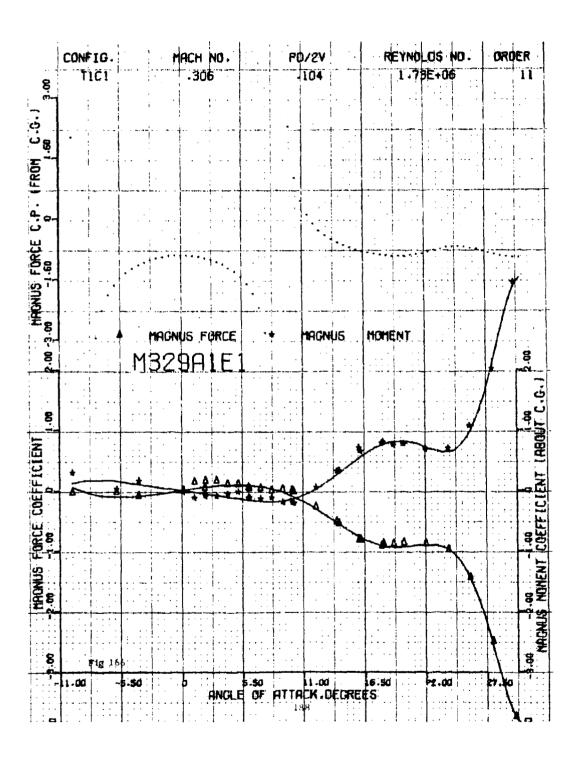






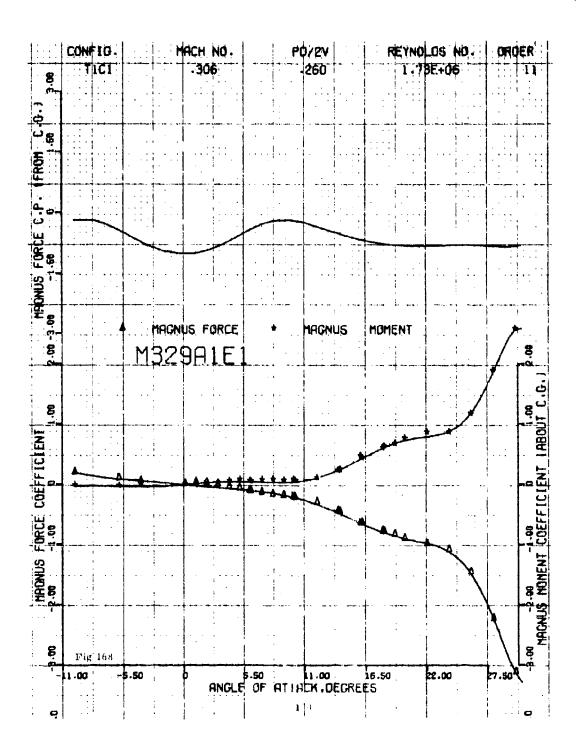


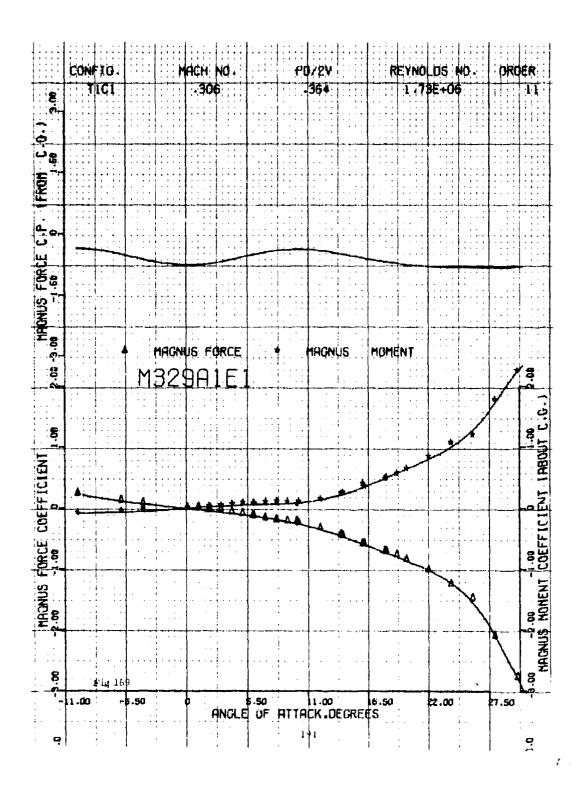




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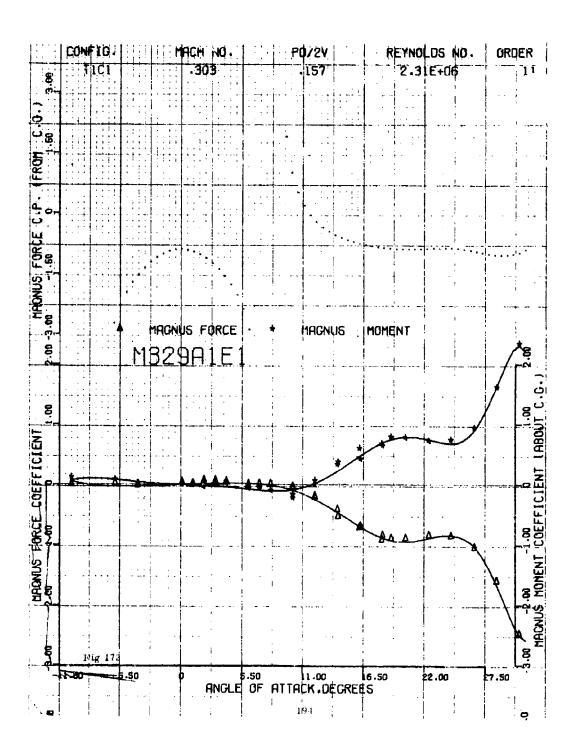


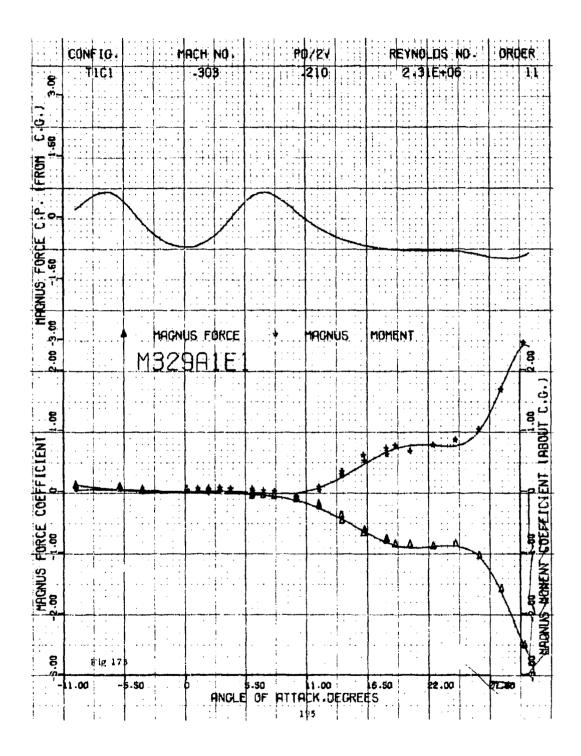


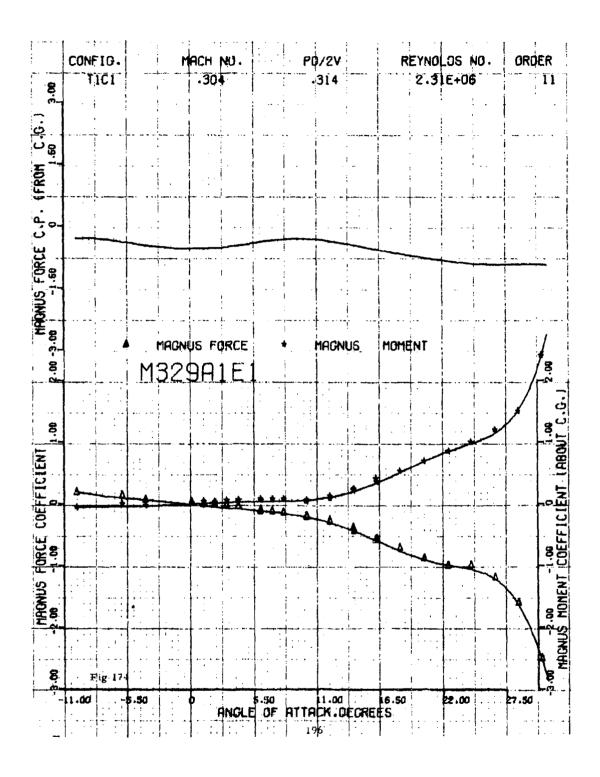
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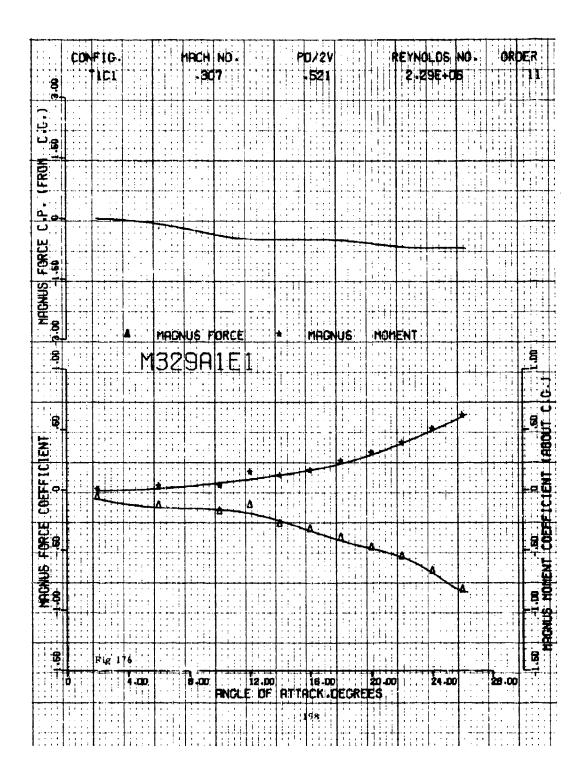




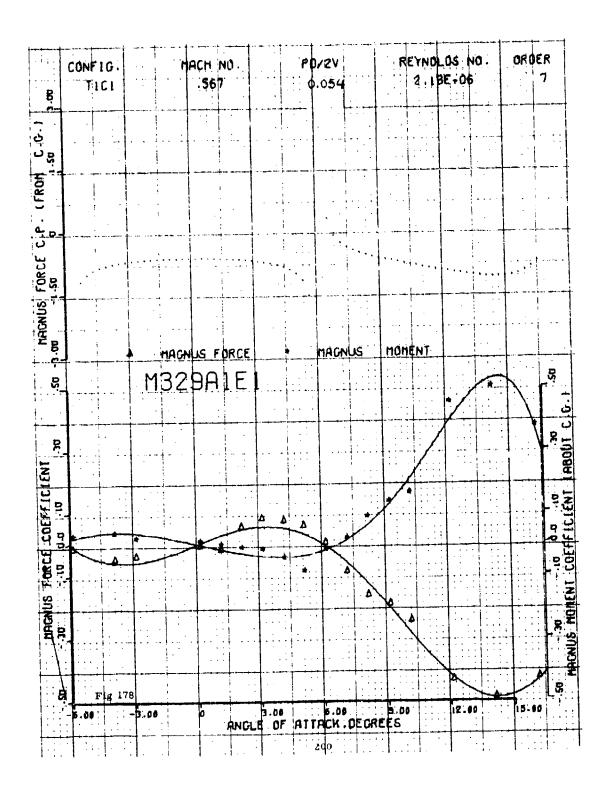


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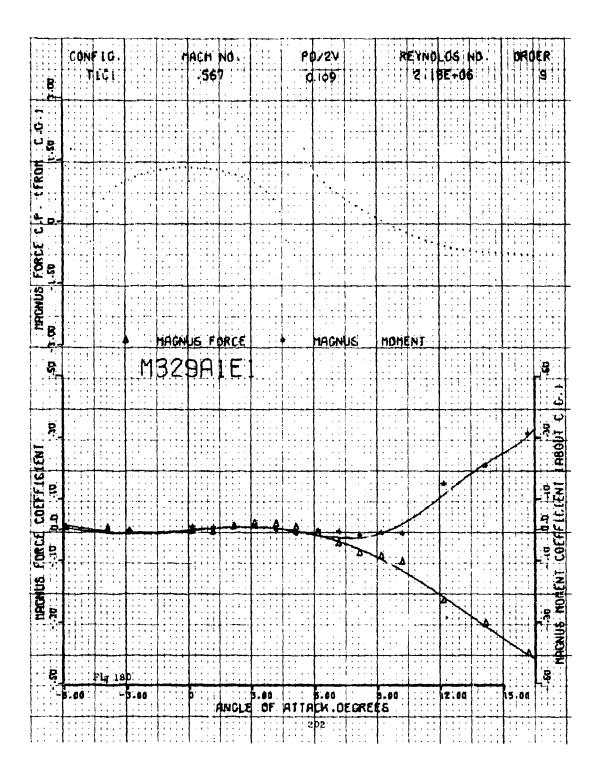
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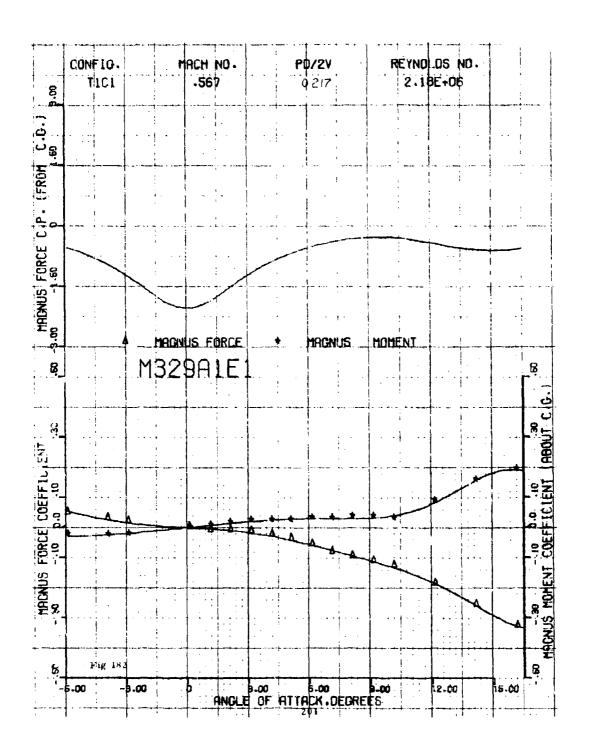
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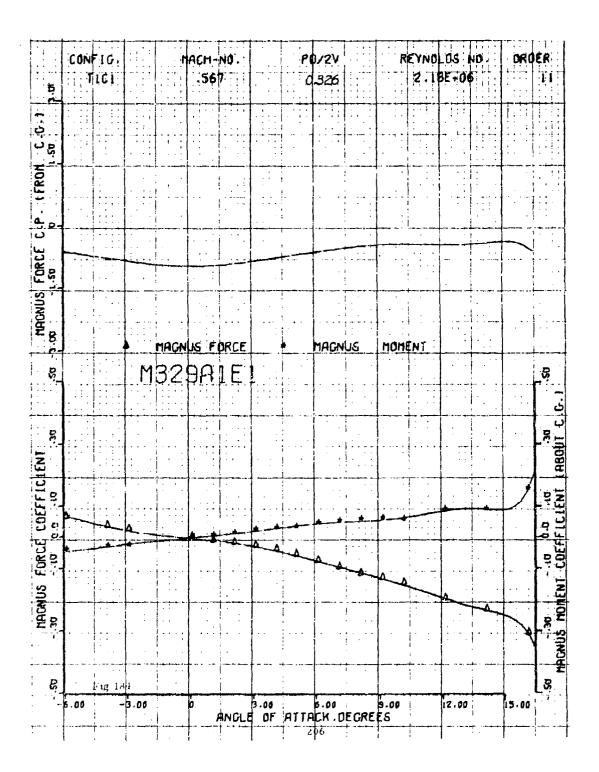
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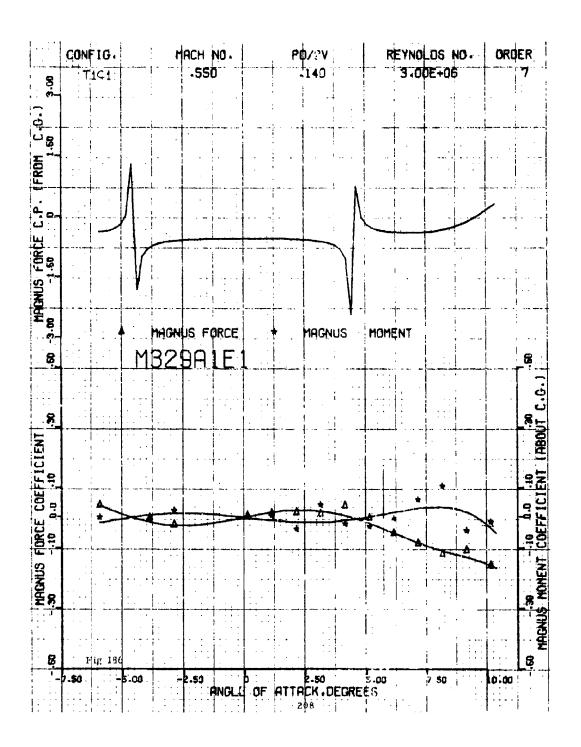
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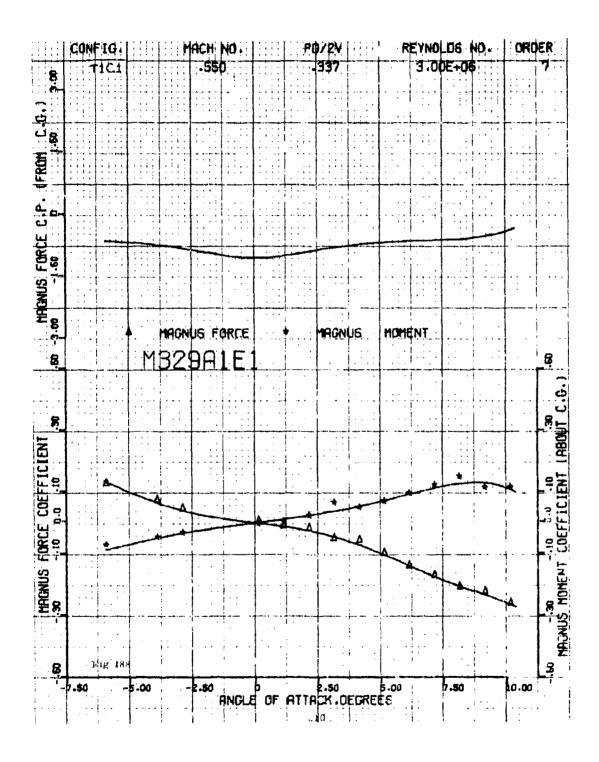
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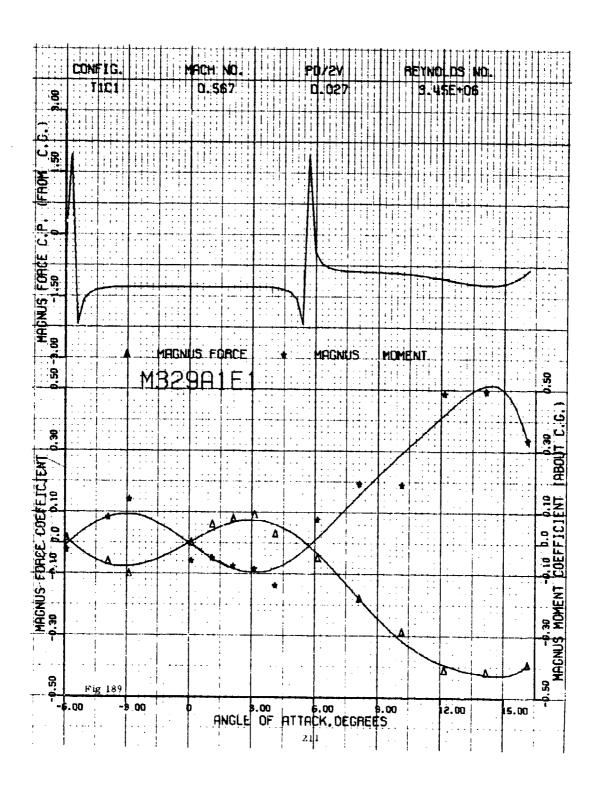
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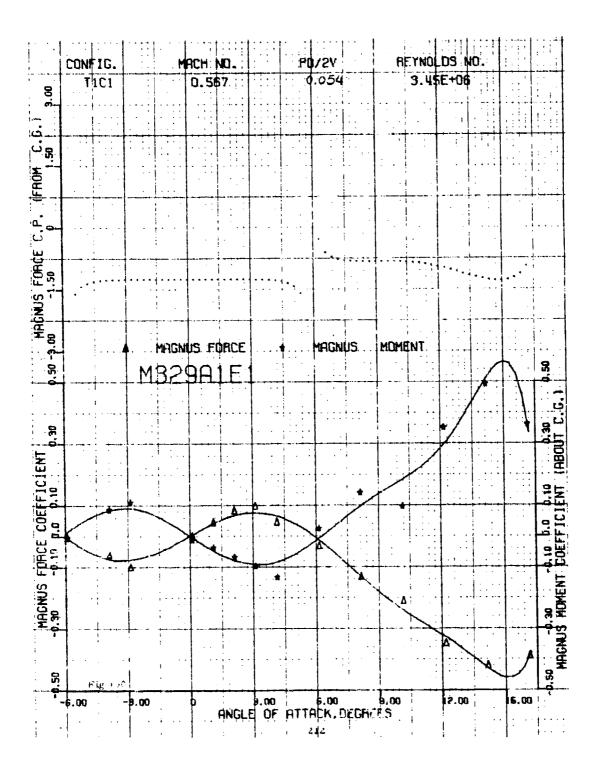
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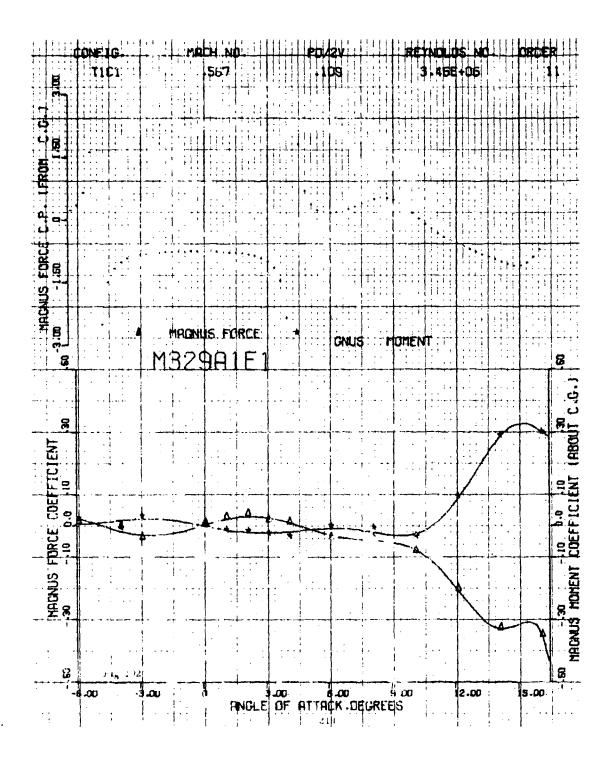


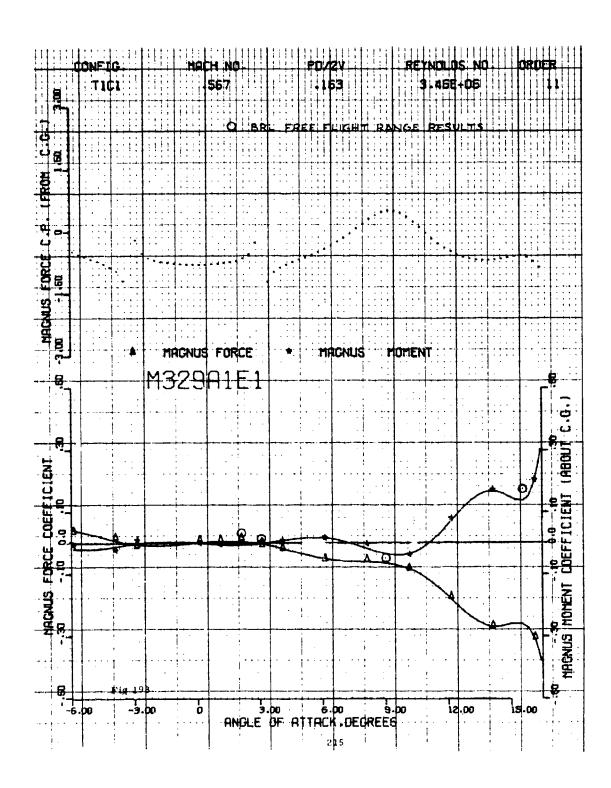


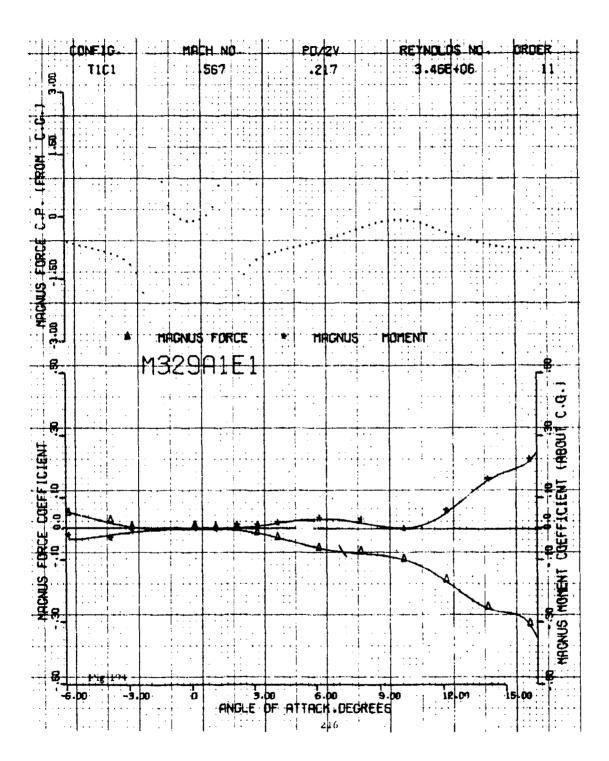
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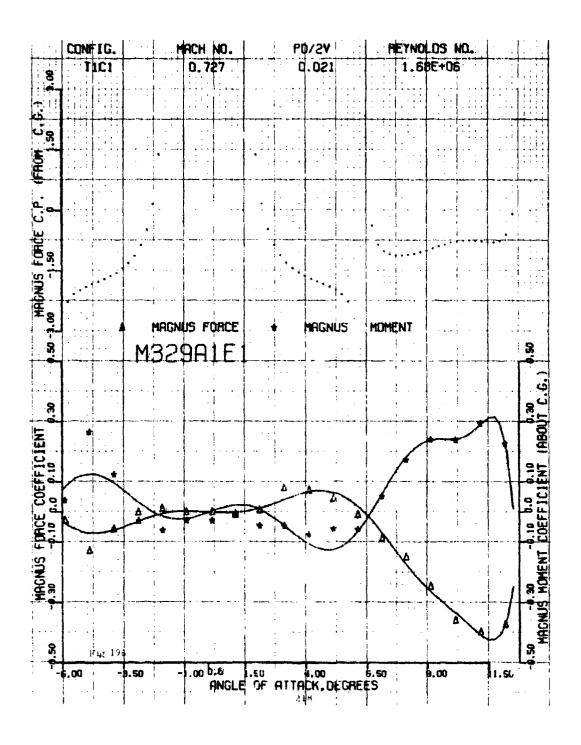
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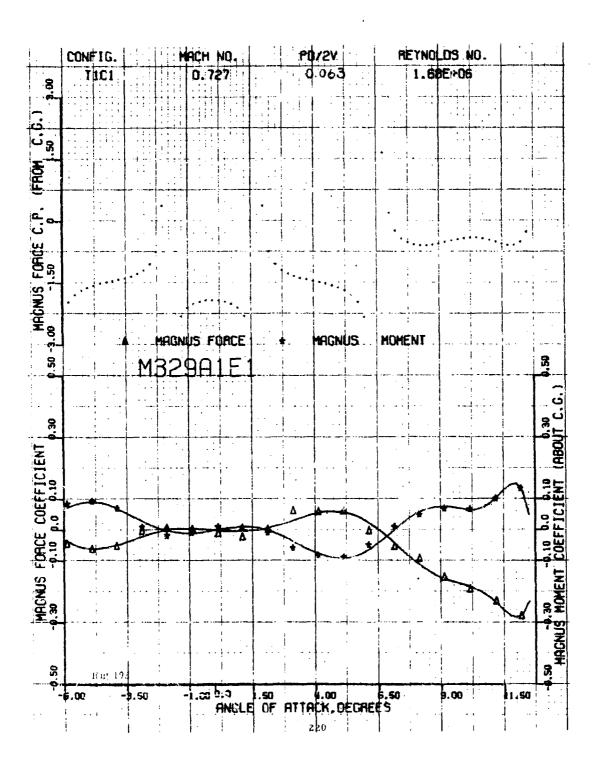
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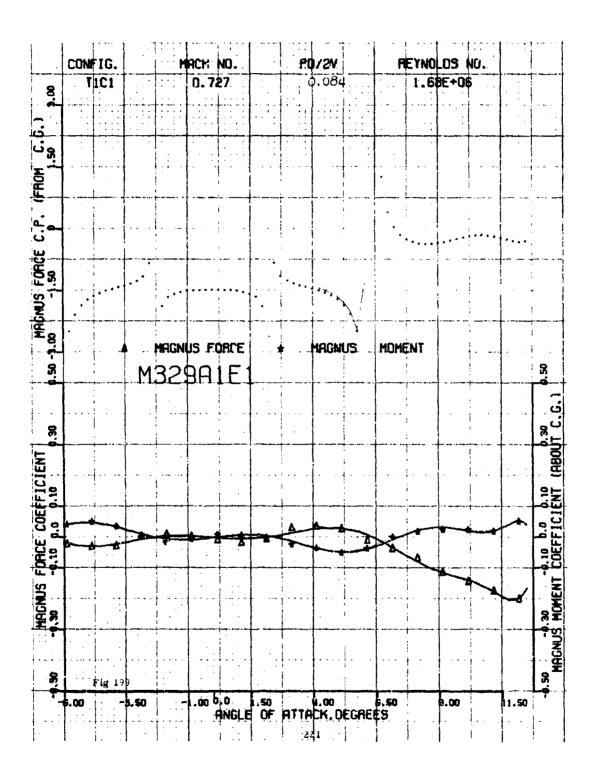


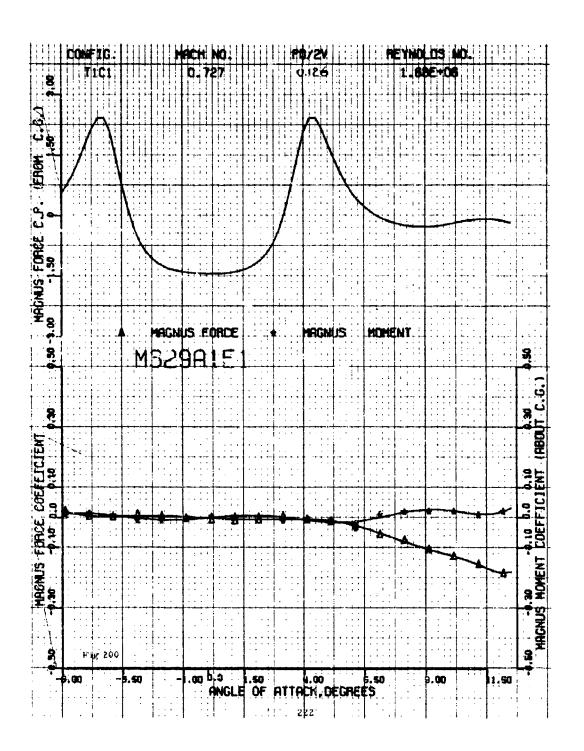
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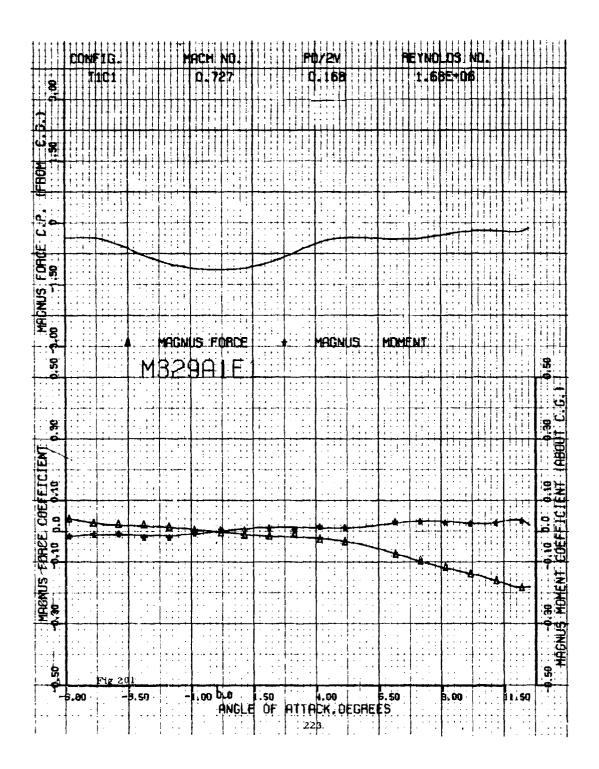
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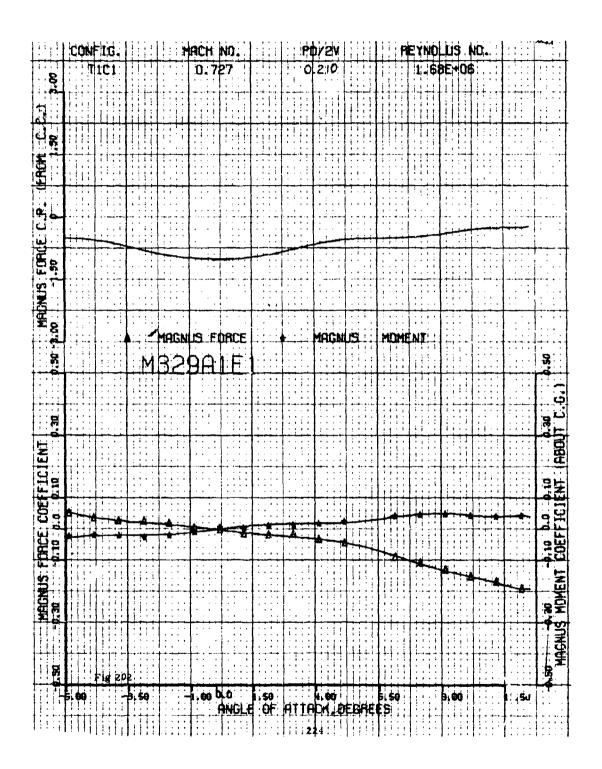
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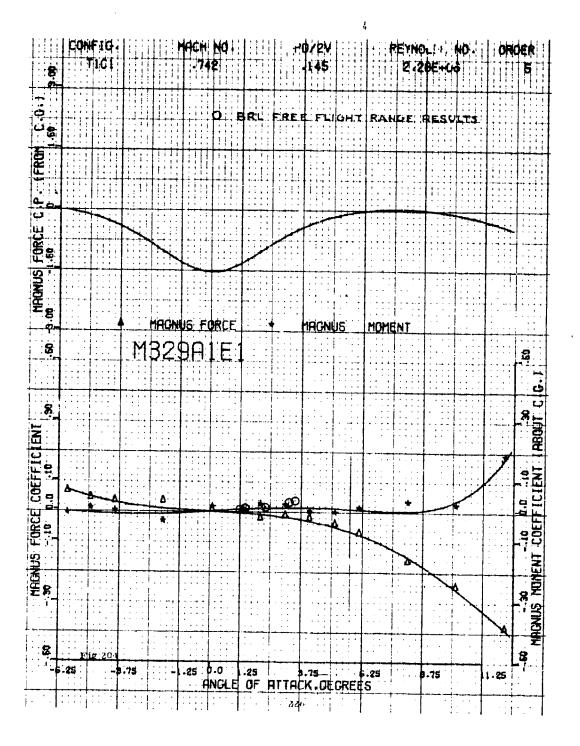


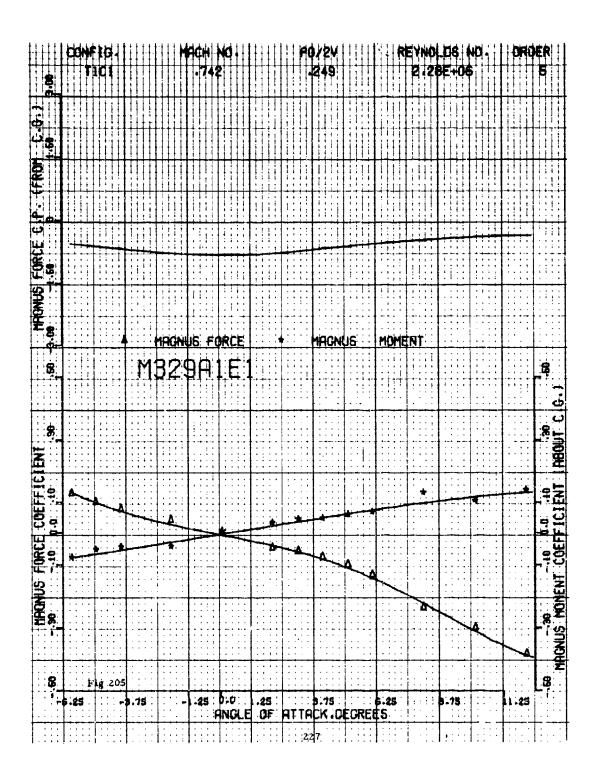


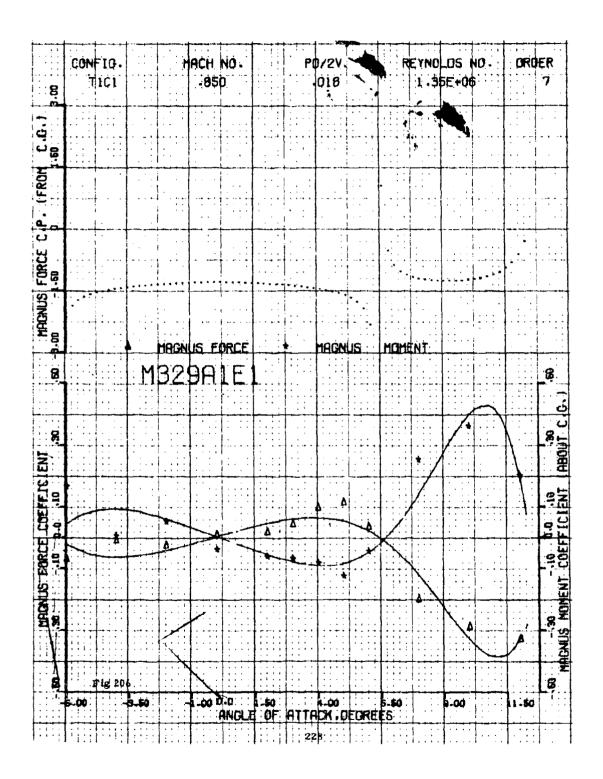




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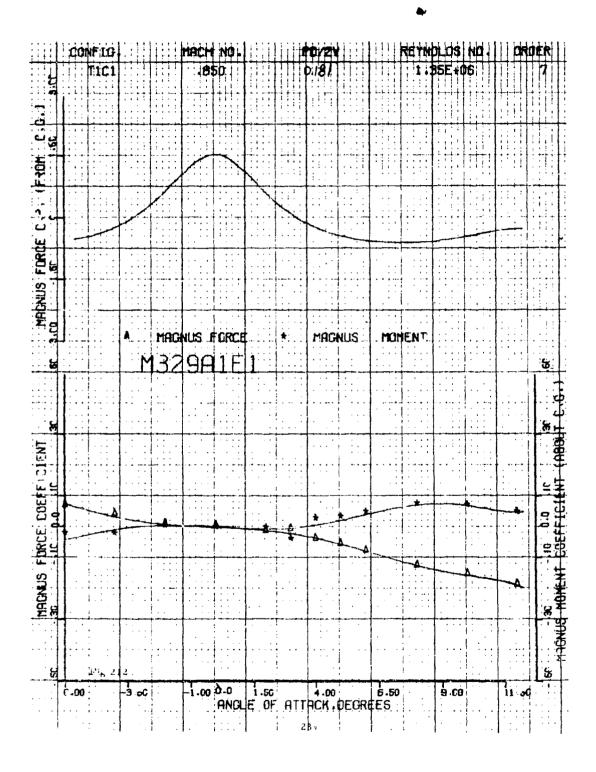
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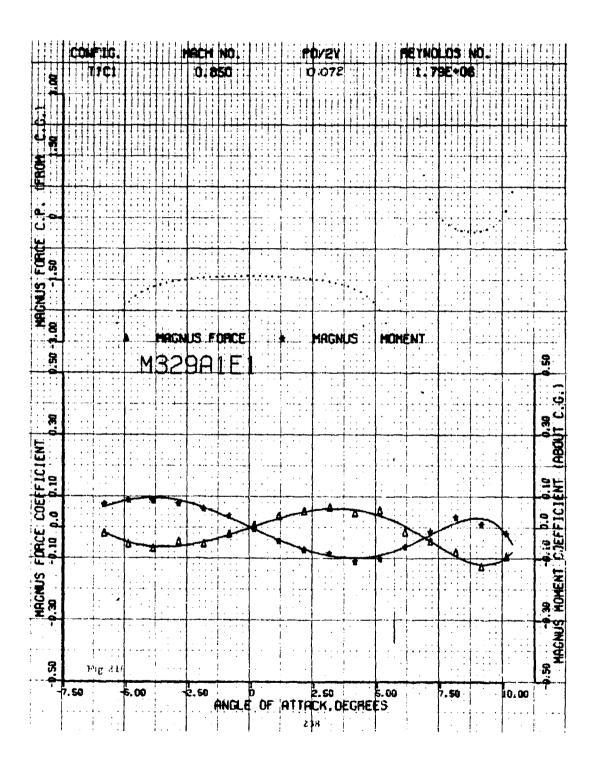


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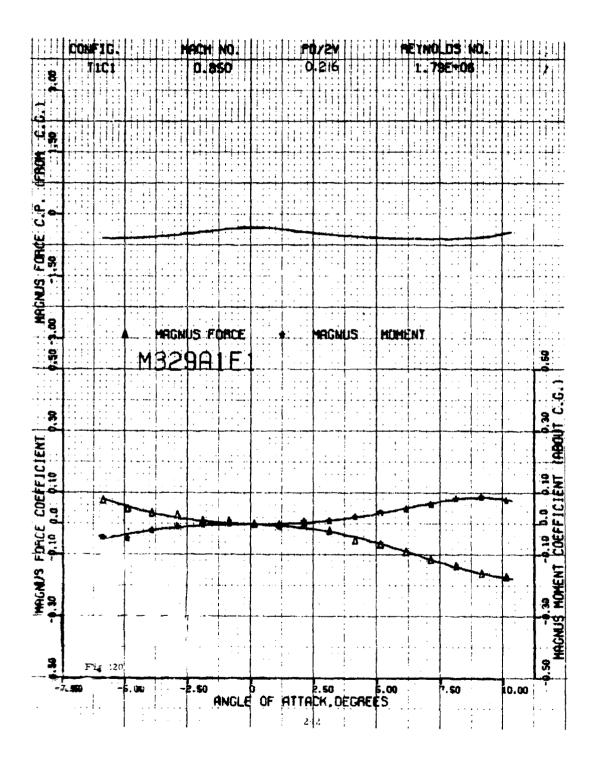
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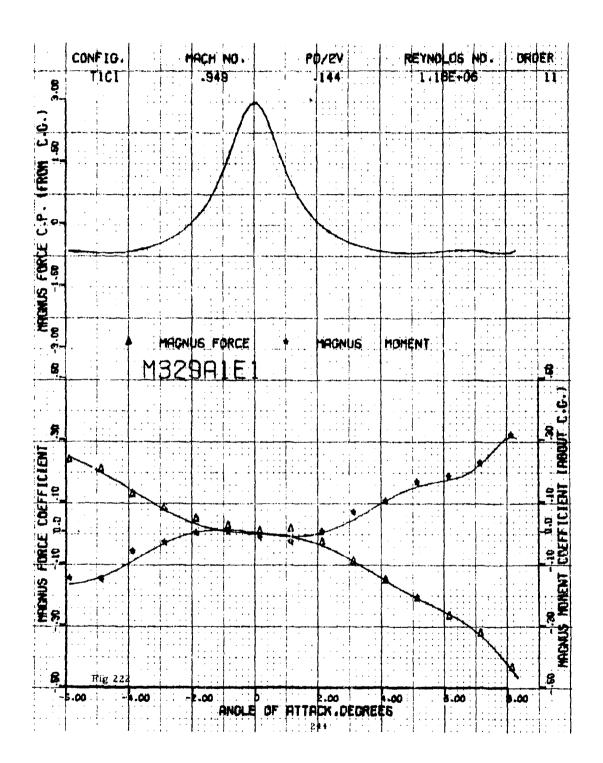
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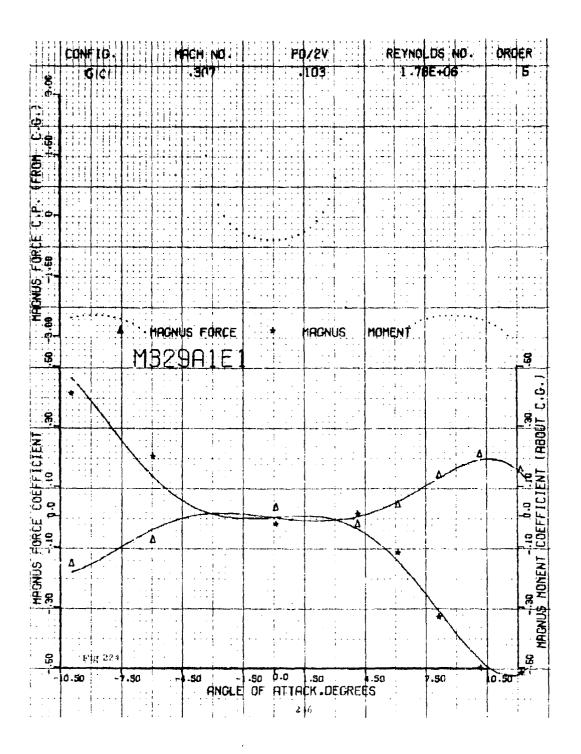


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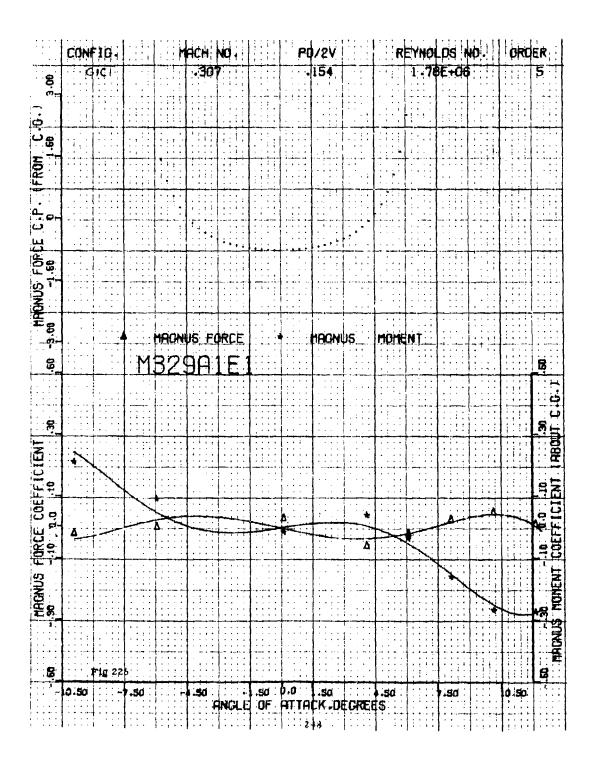
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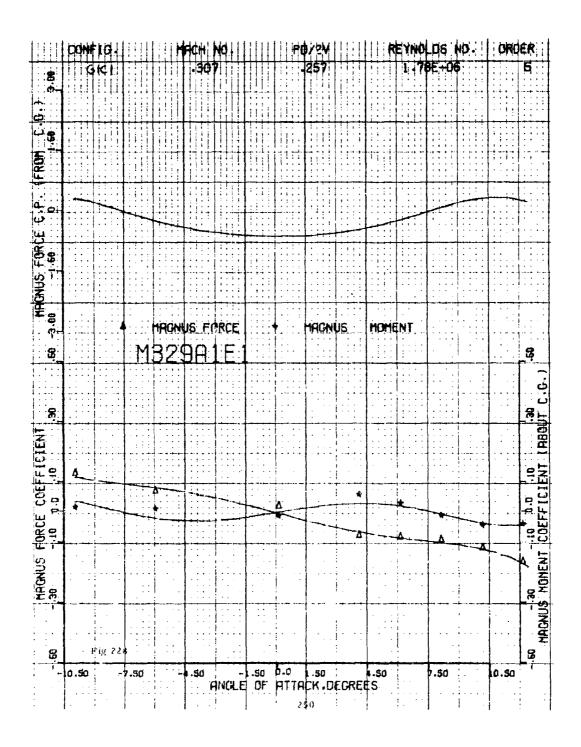


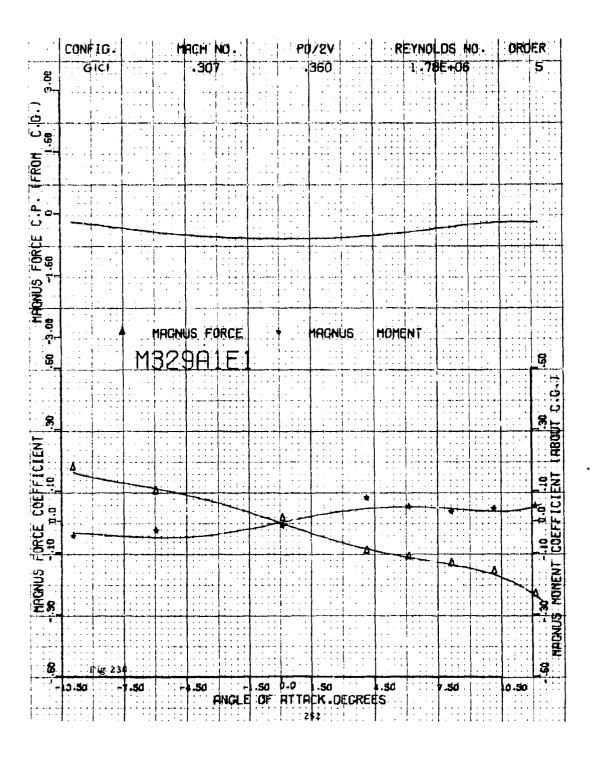


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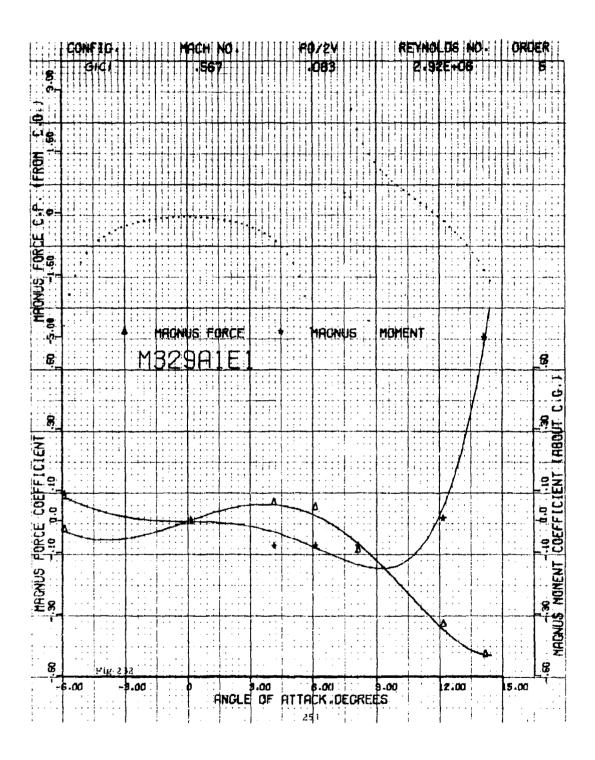


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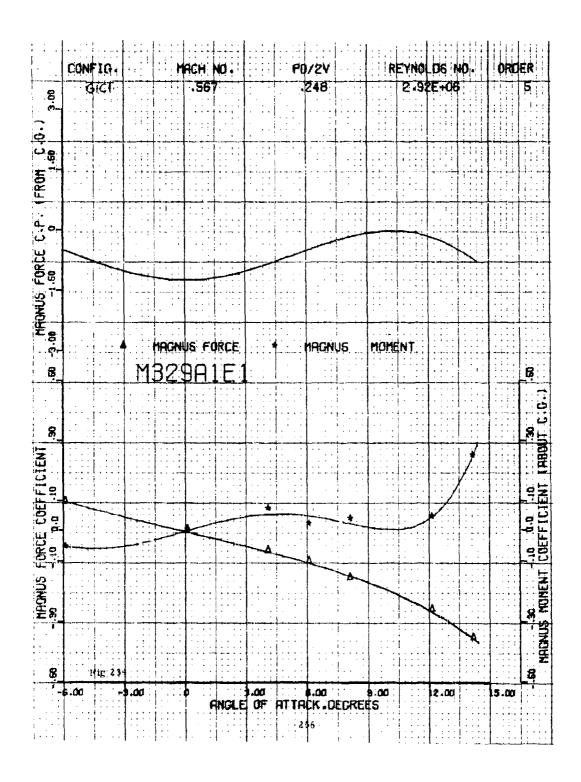




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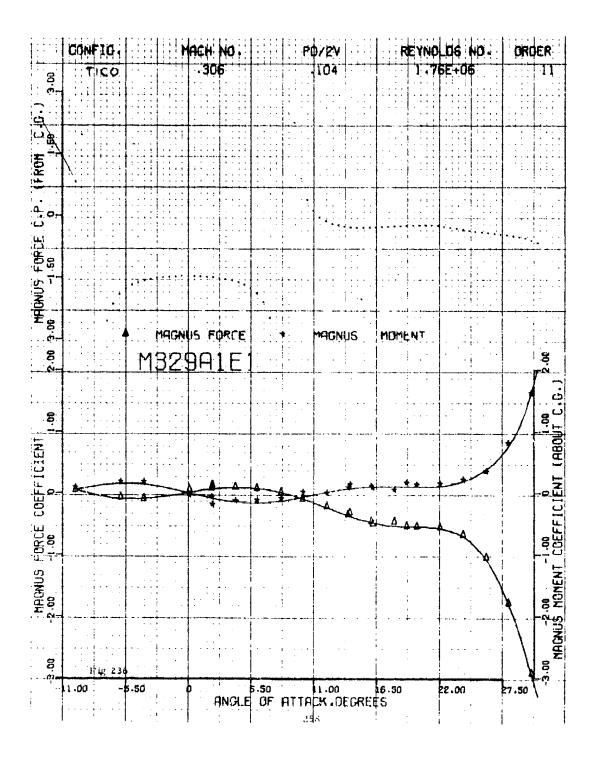


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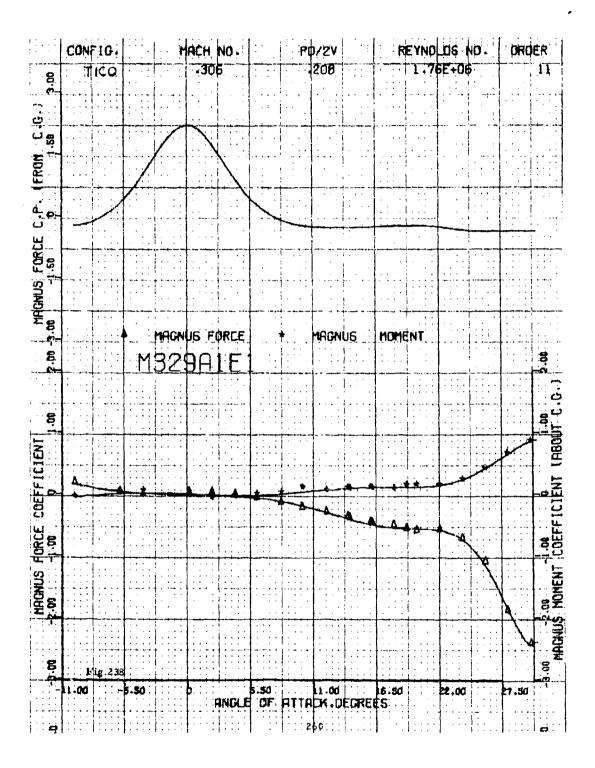


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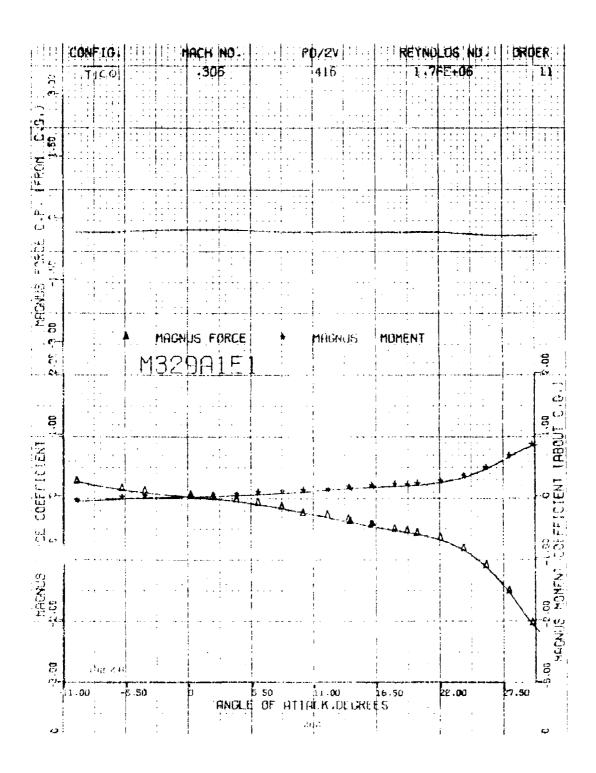
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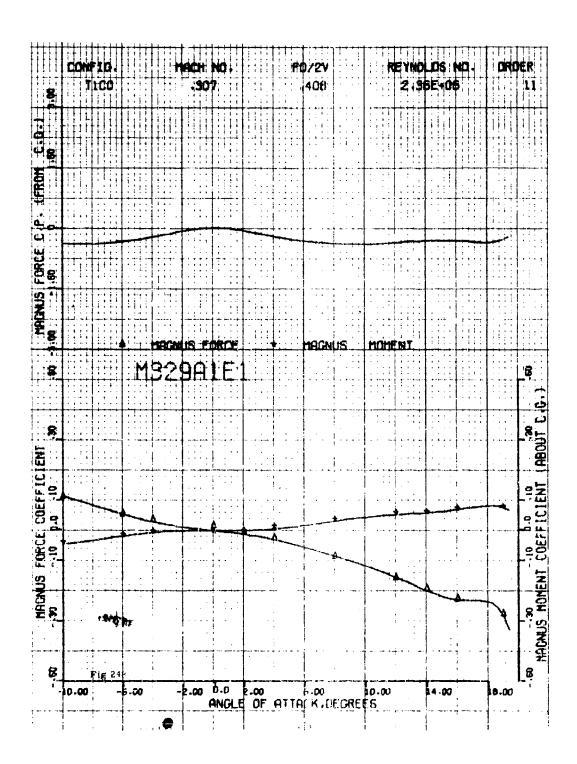
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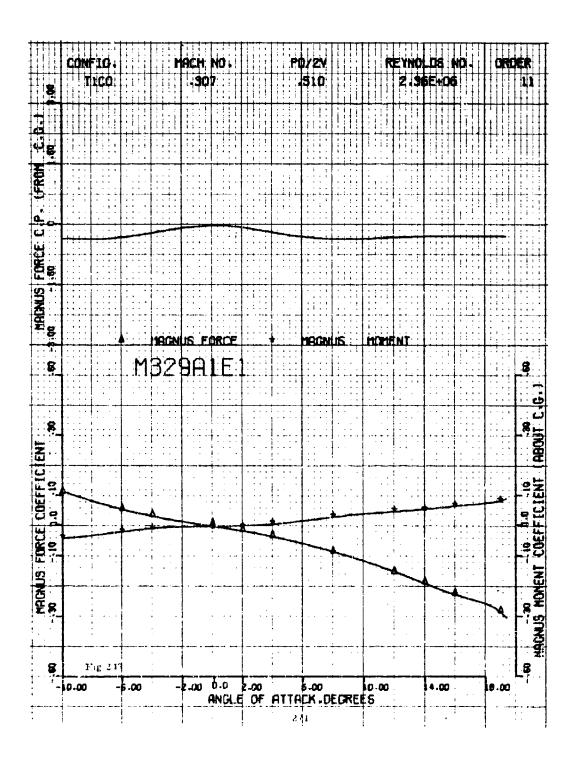
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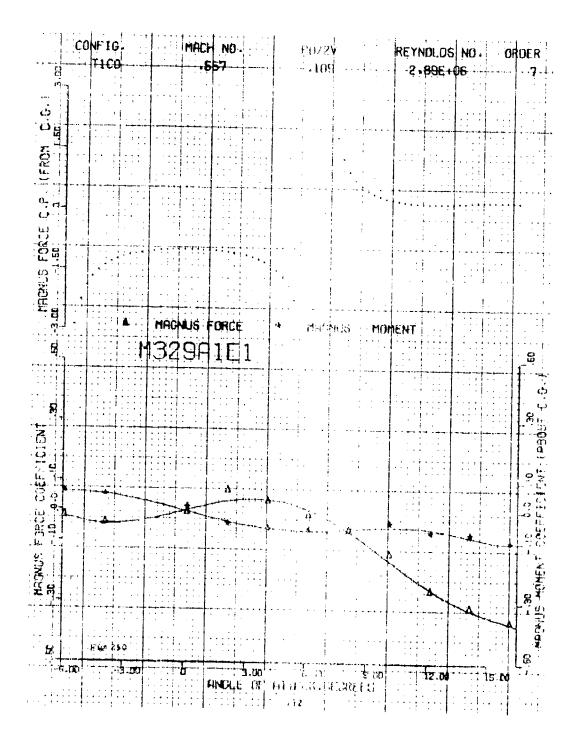
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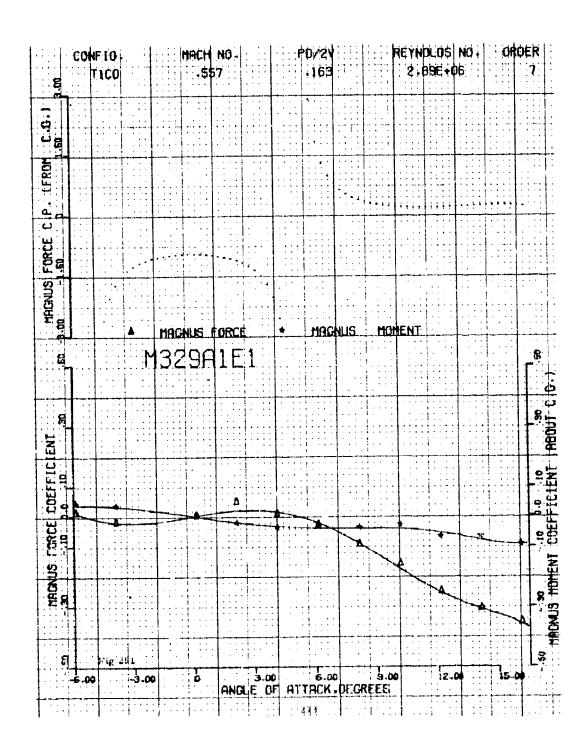
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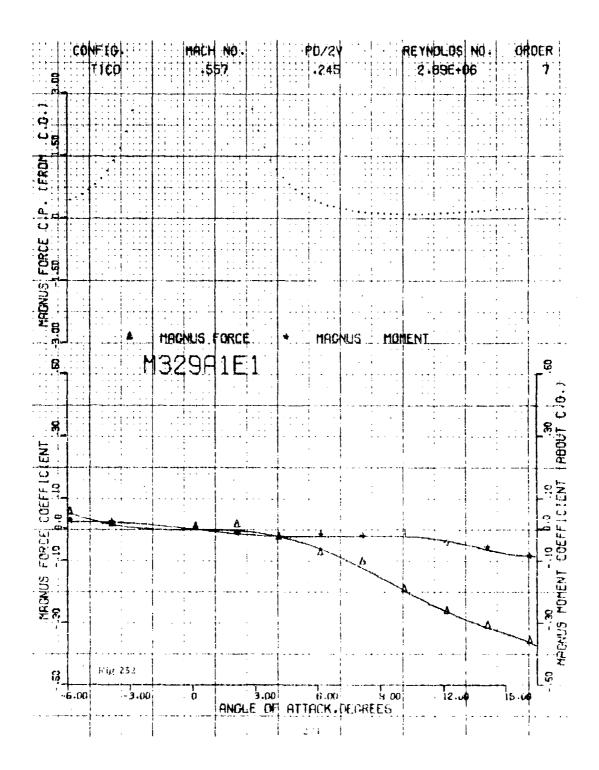
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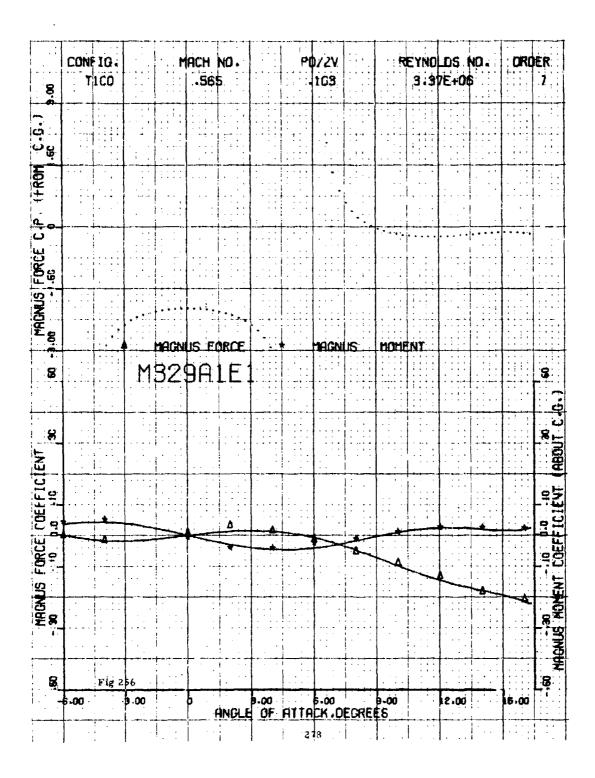
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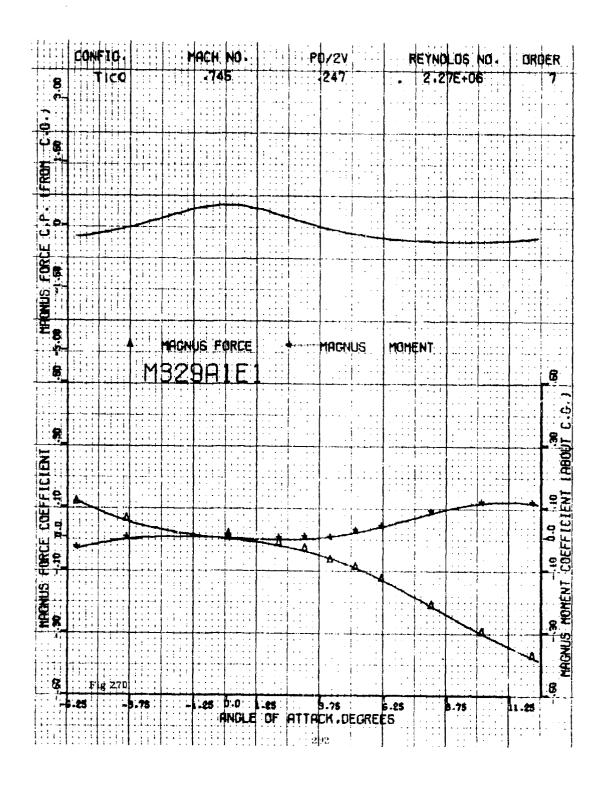
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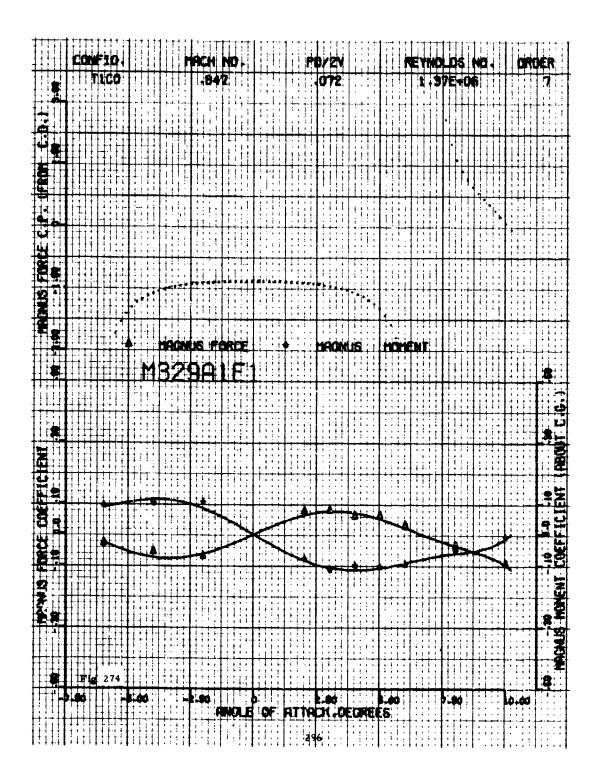
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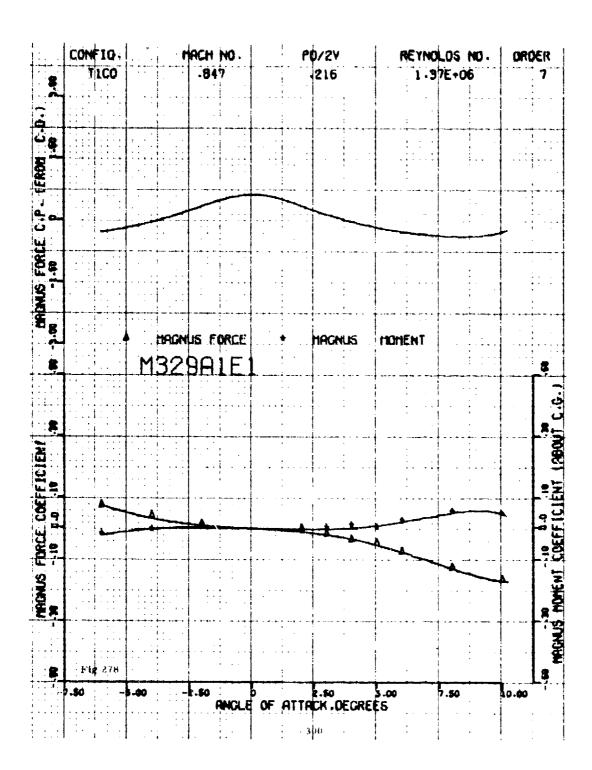
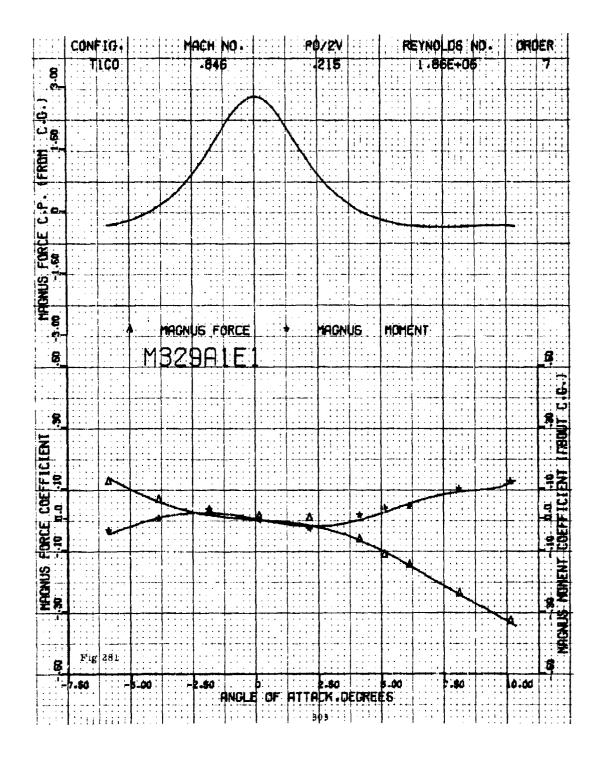
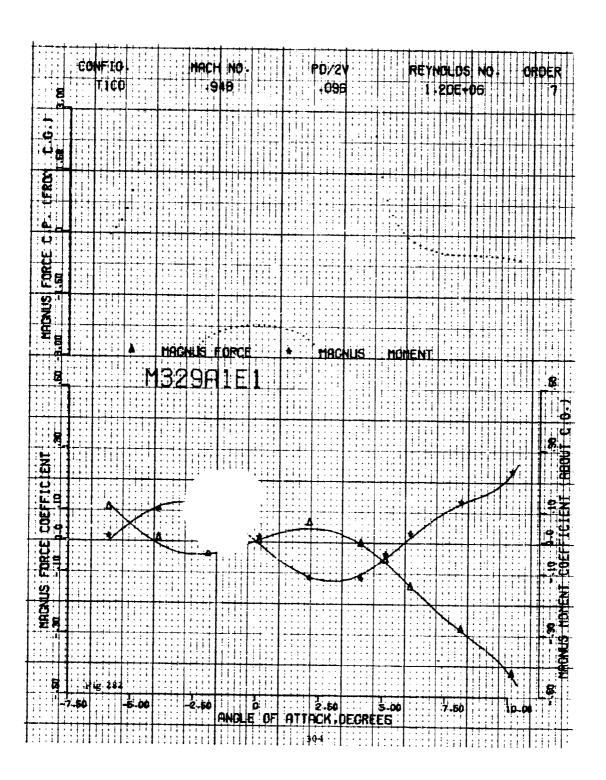


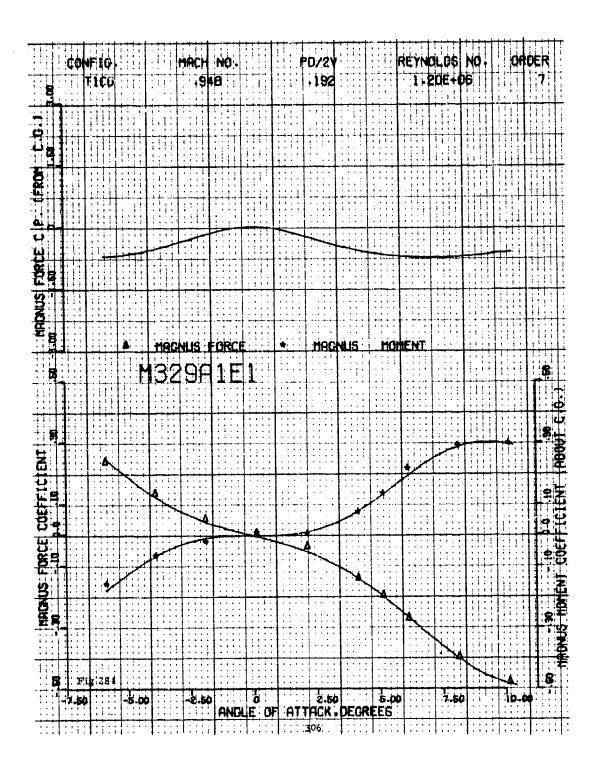
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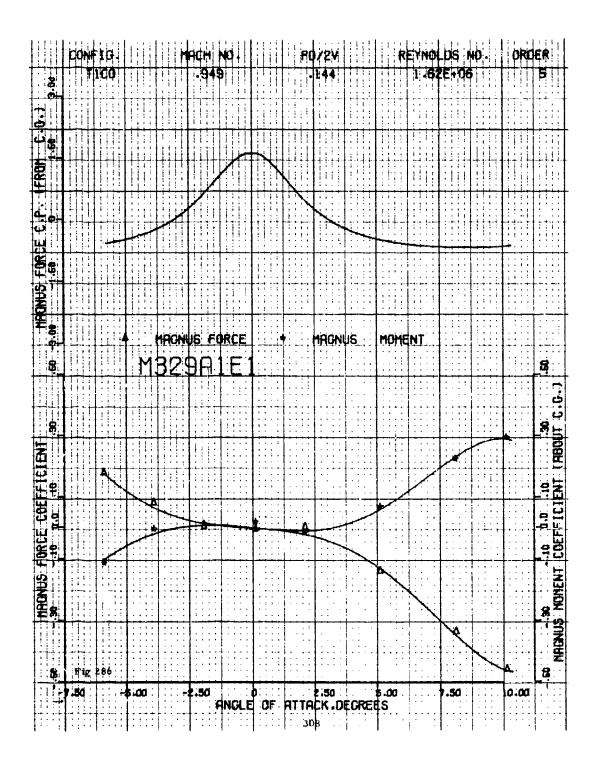
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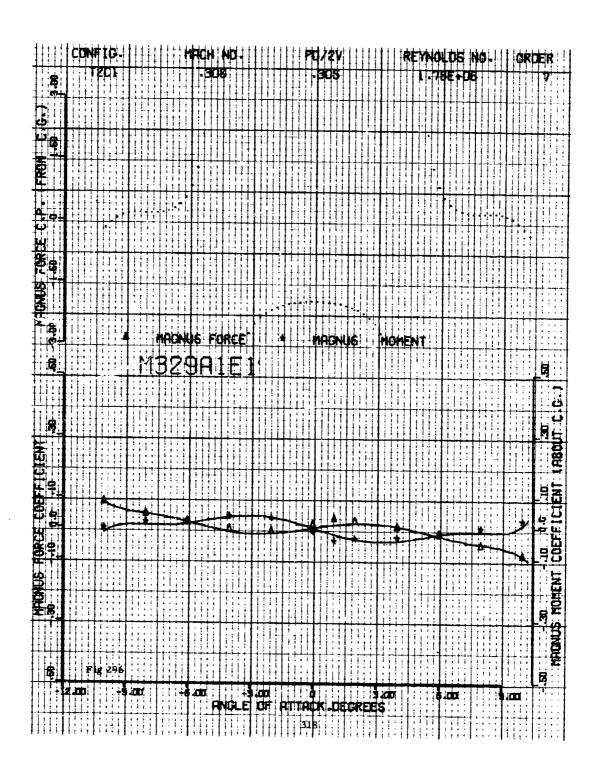
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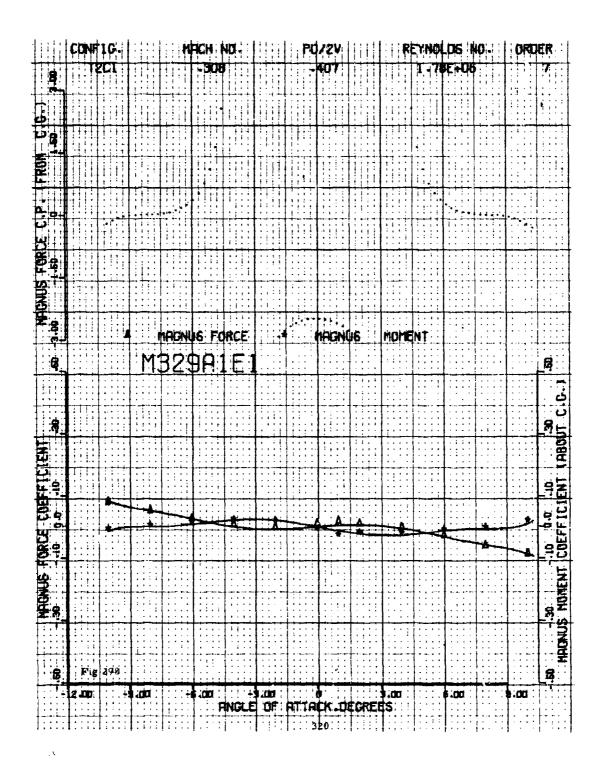
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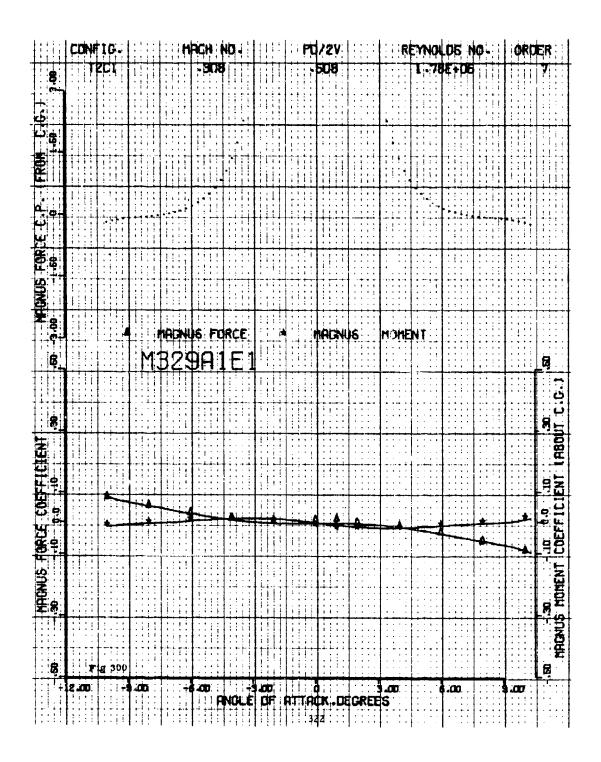
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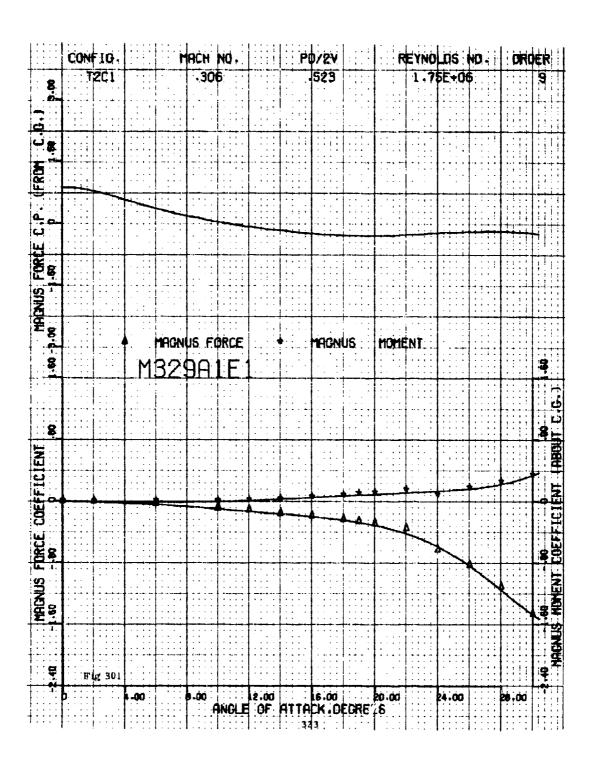
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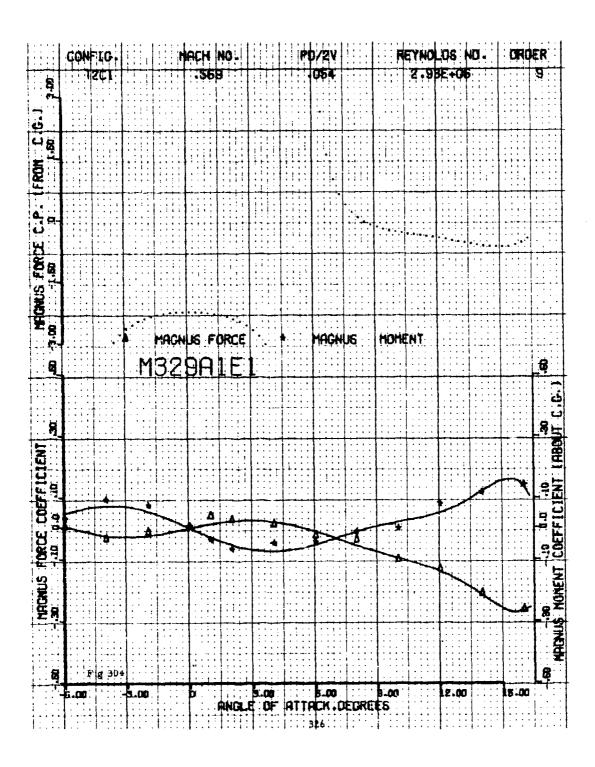


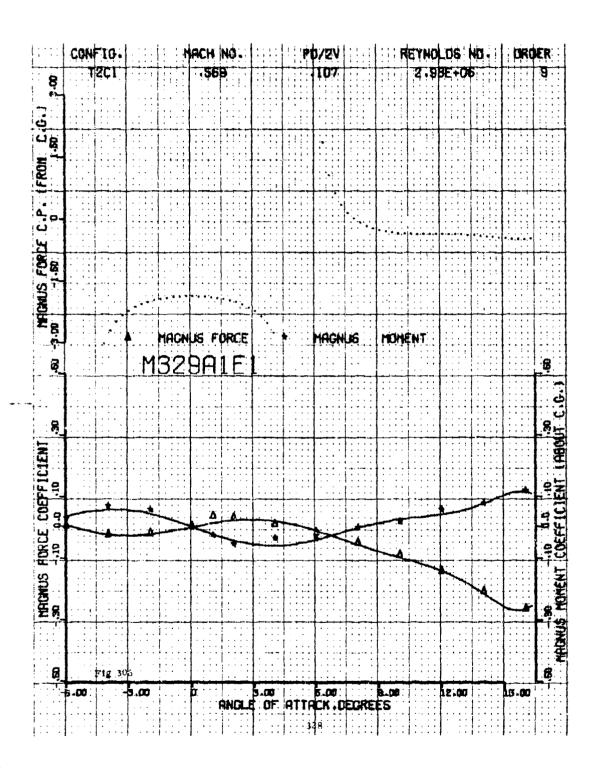


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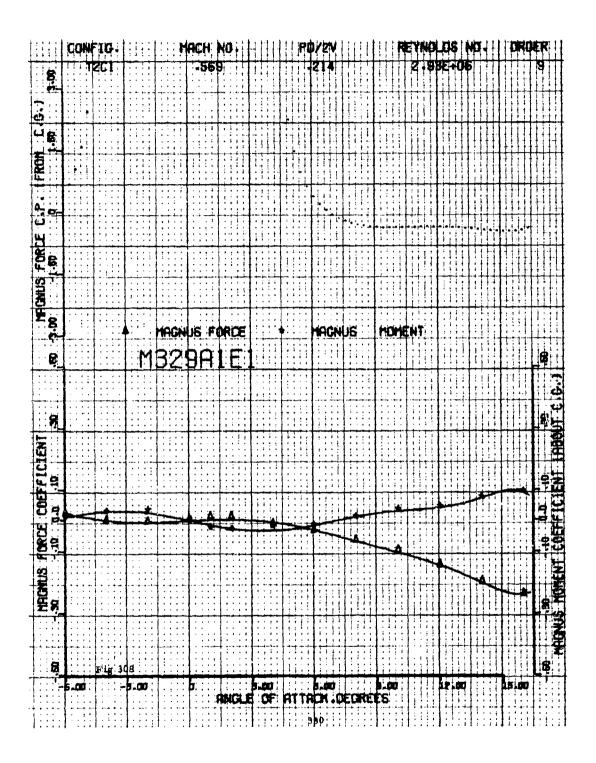
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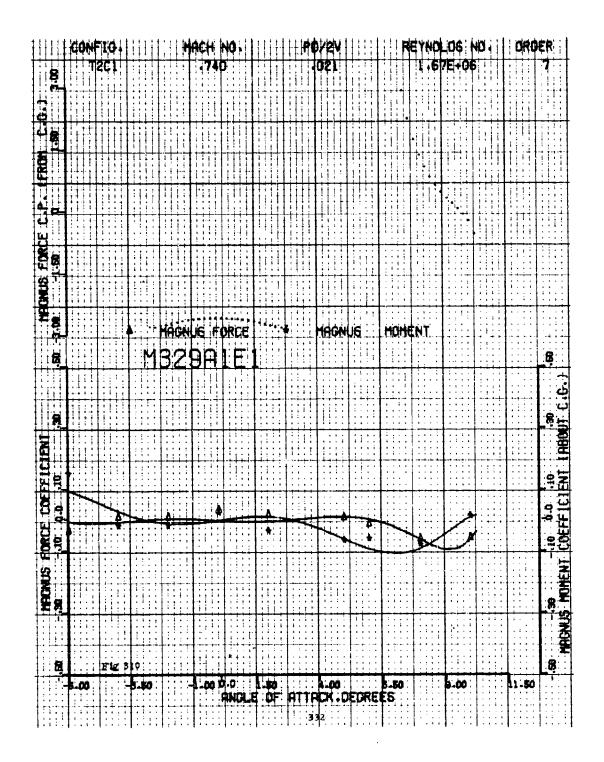


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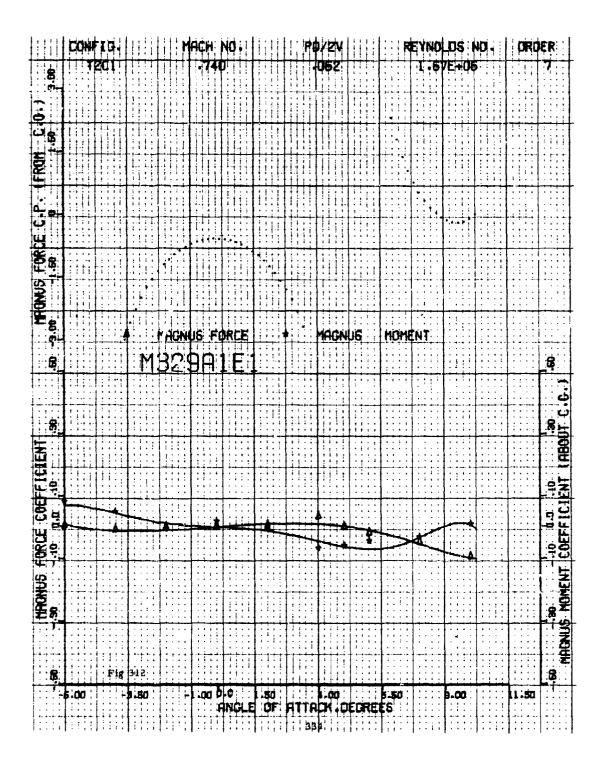
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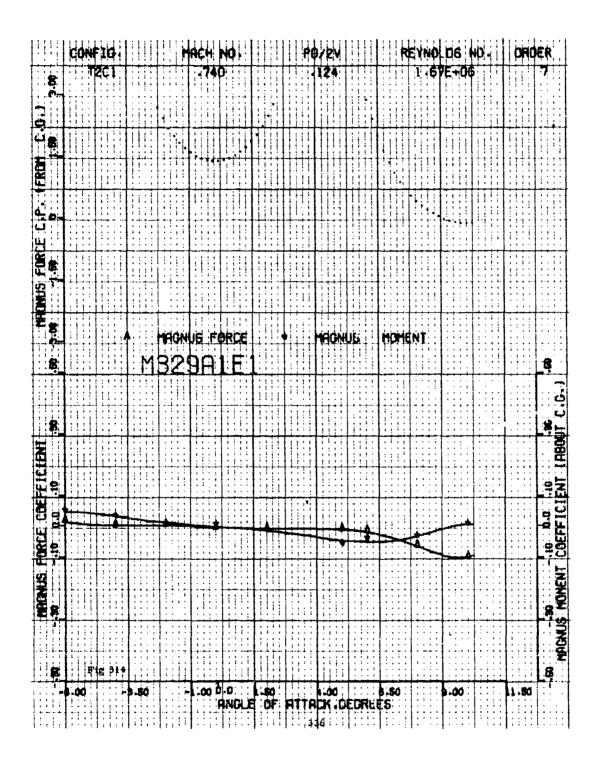
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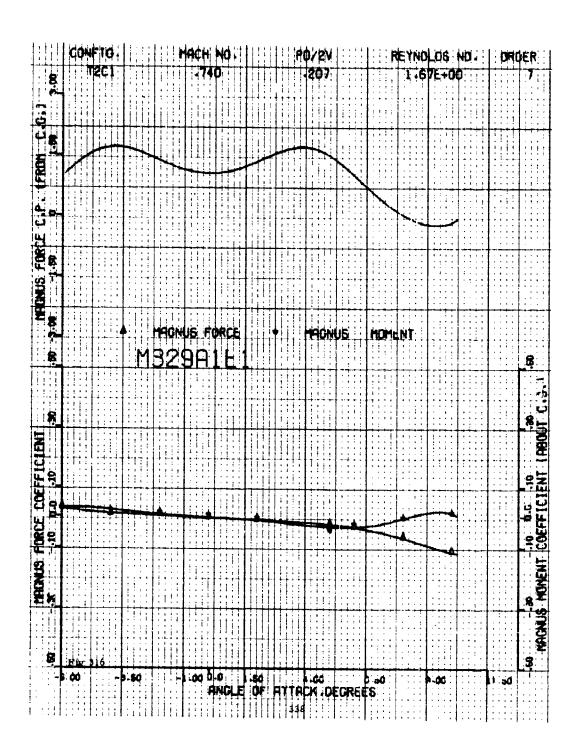


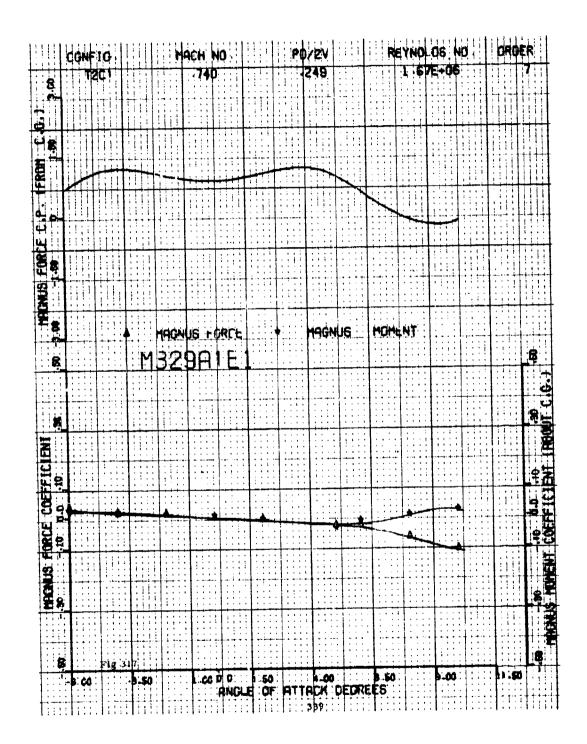
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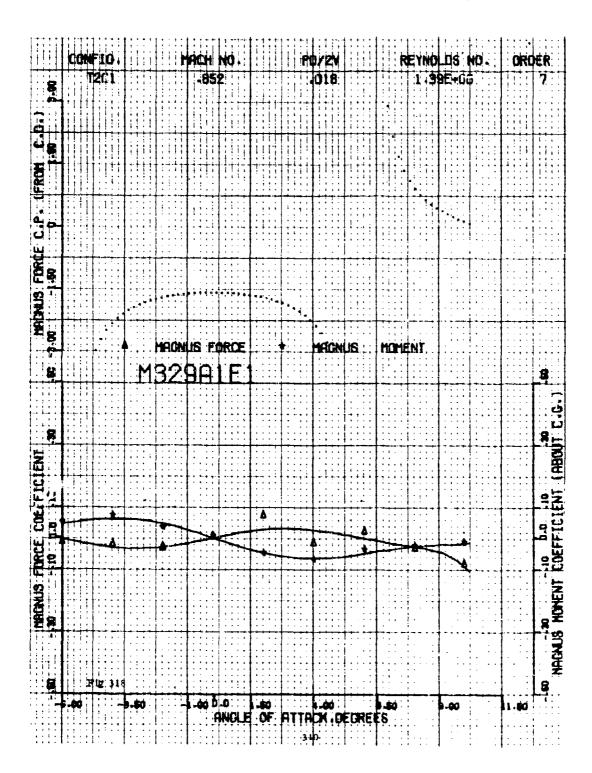


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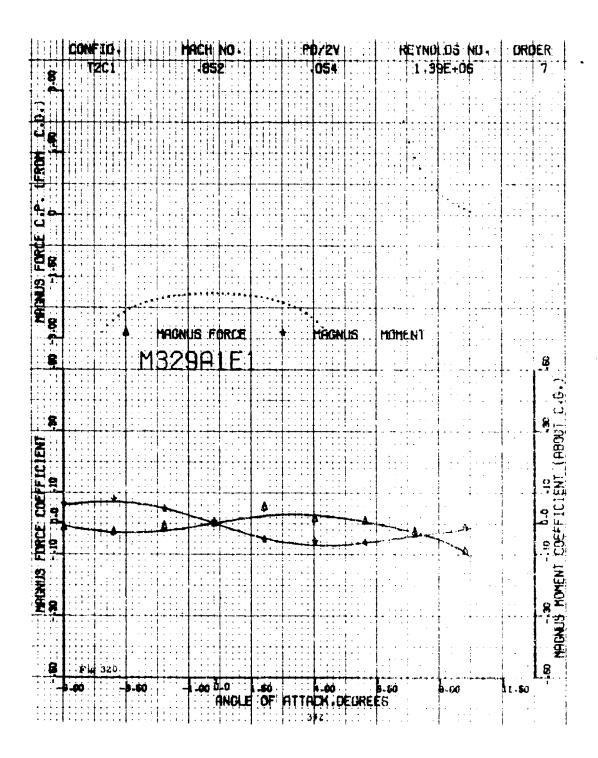






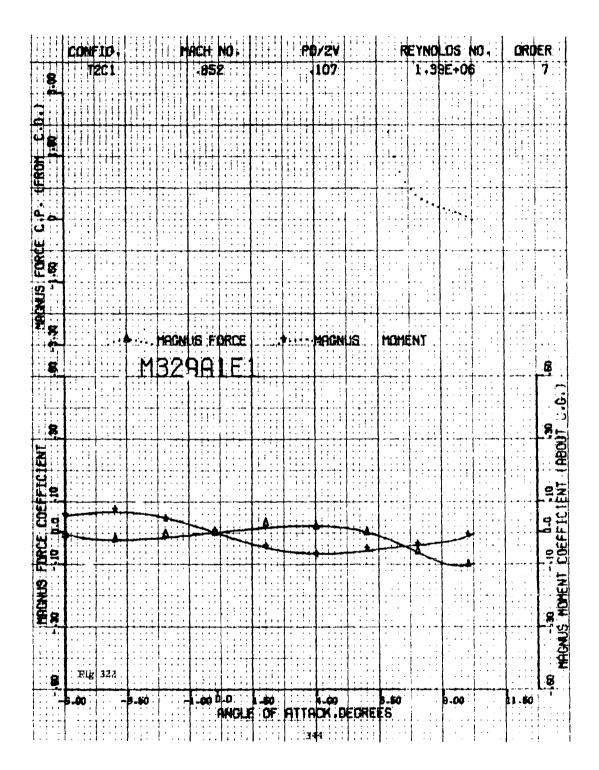


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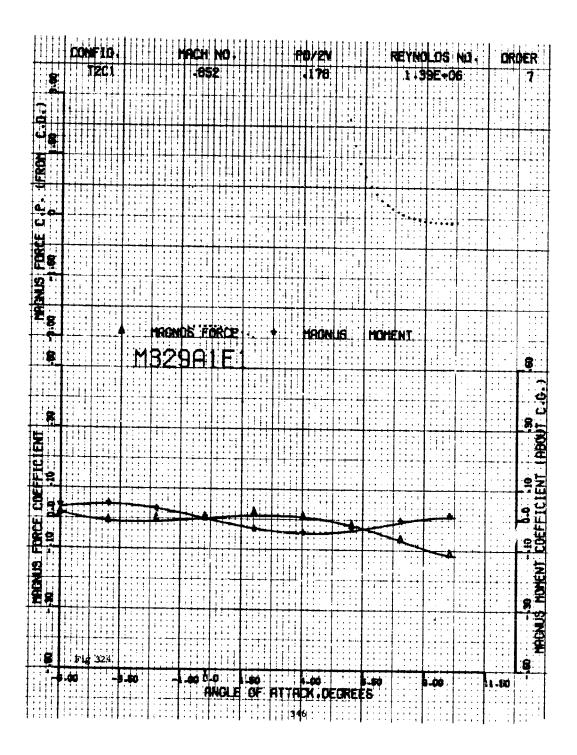
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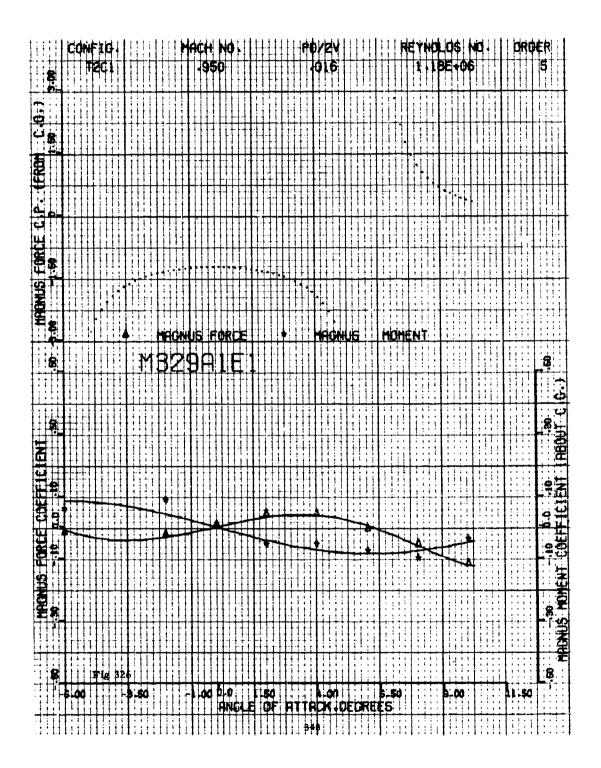


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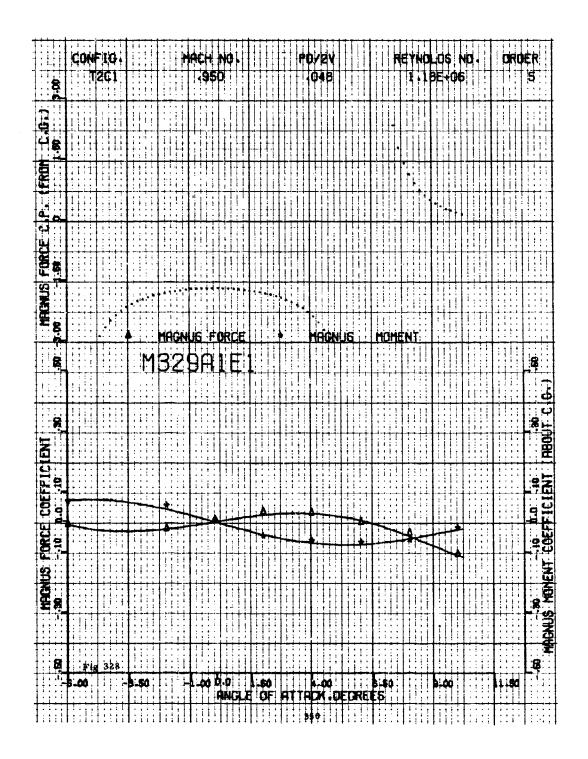


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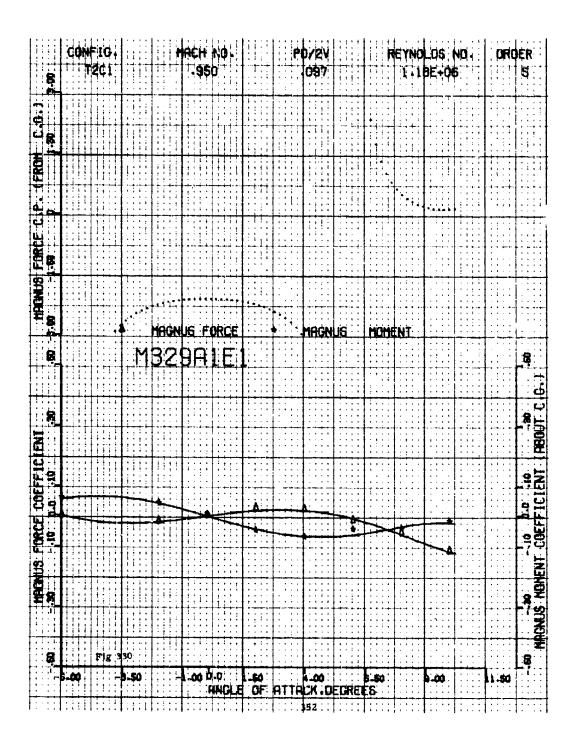


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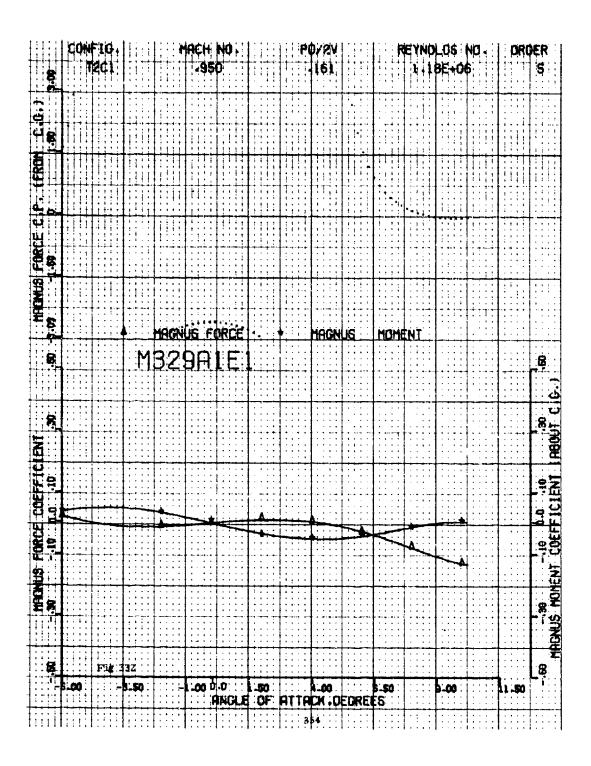


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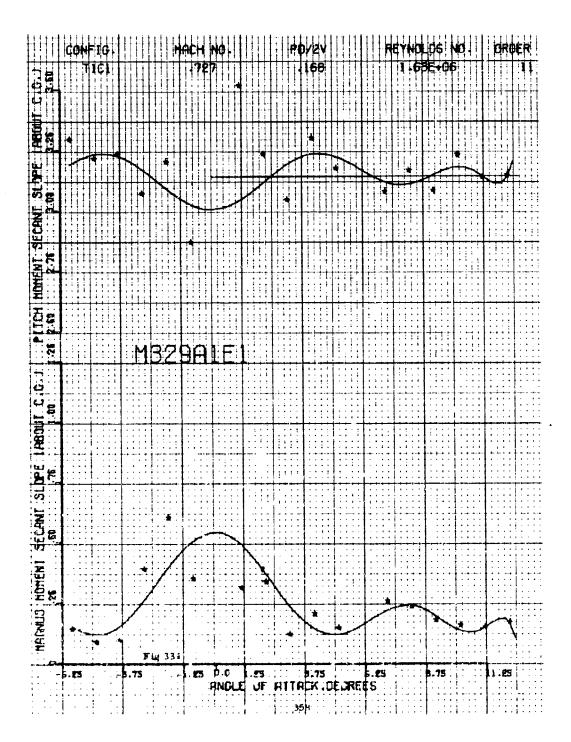


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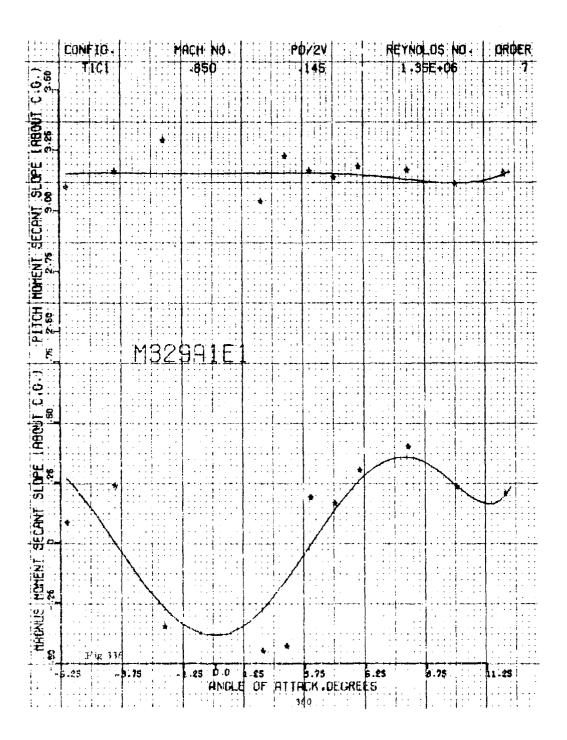
Figures 334 through 357

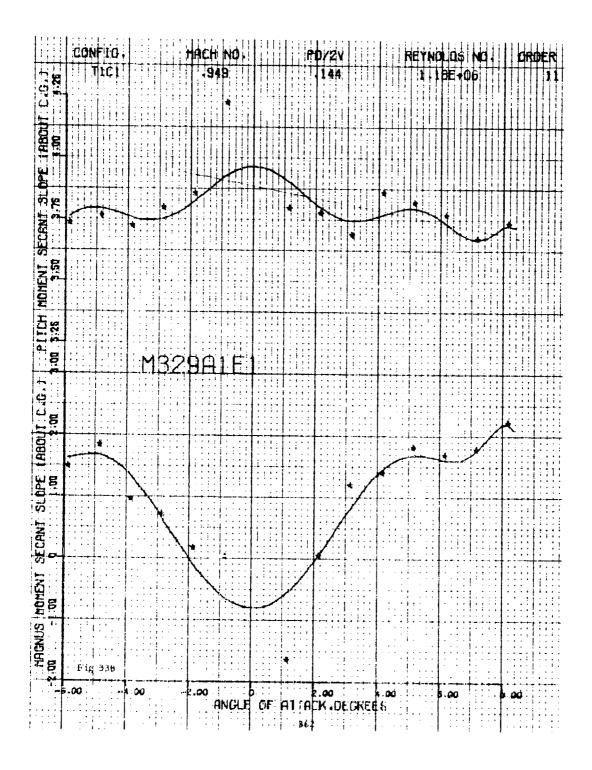
Pitching moment secant slope, Magnus moment secant slope vs angle of attack

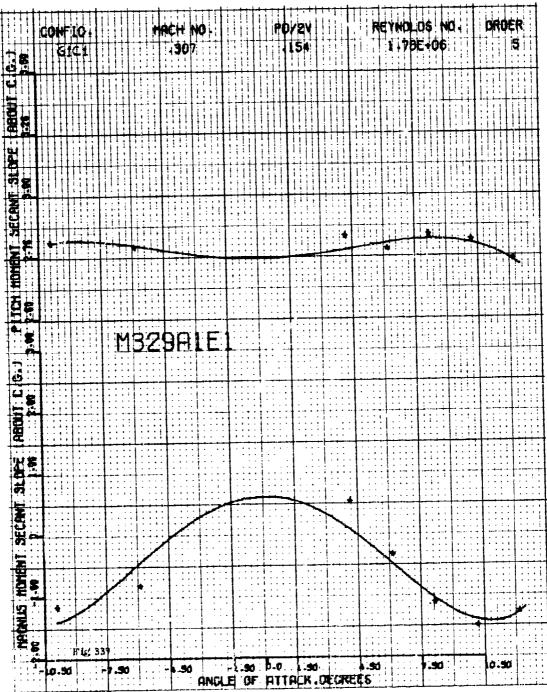
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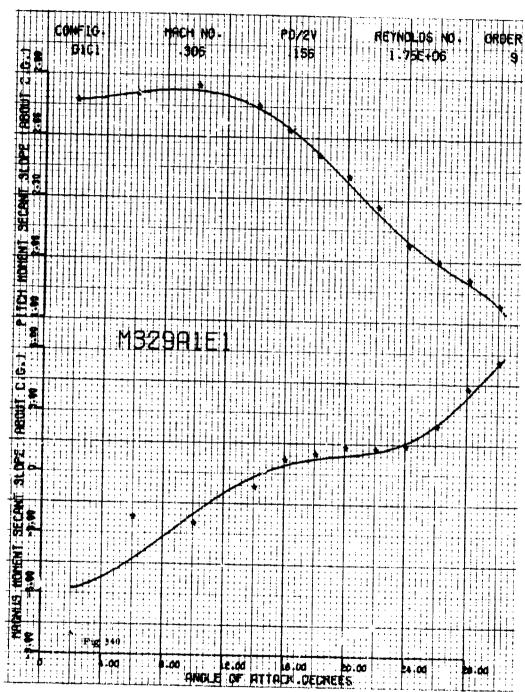


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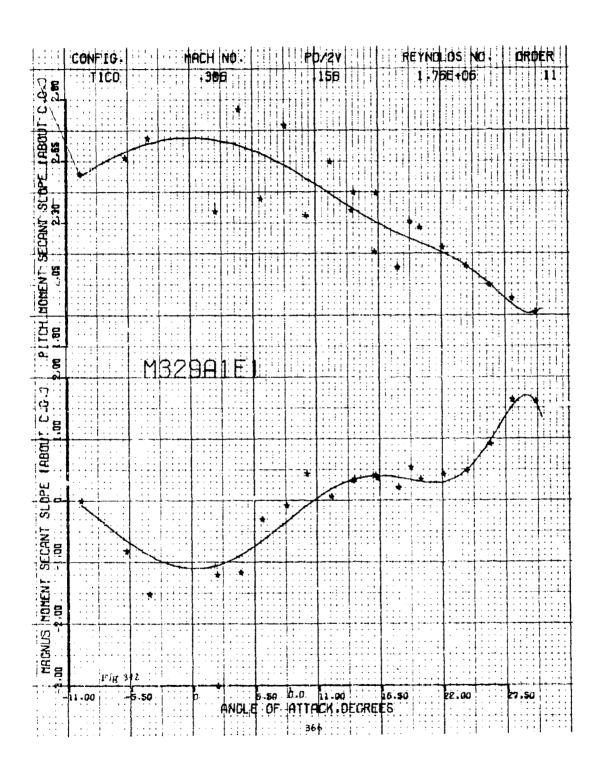






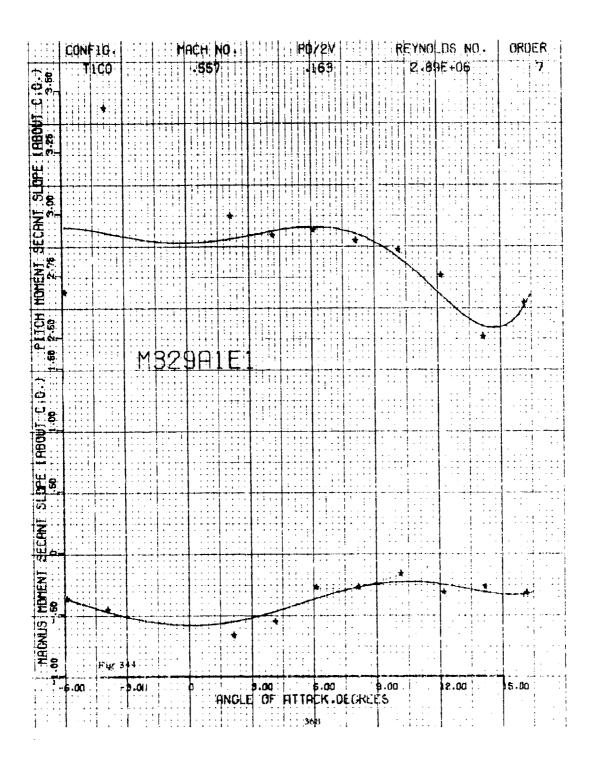


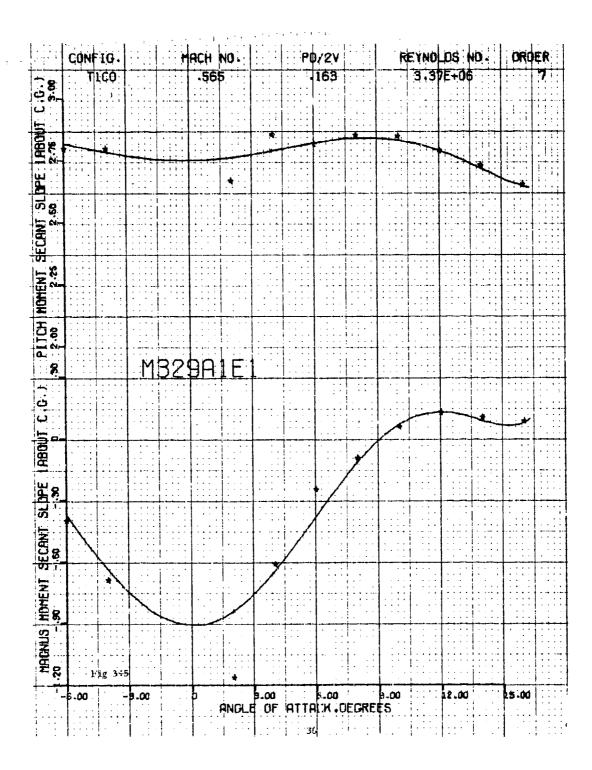
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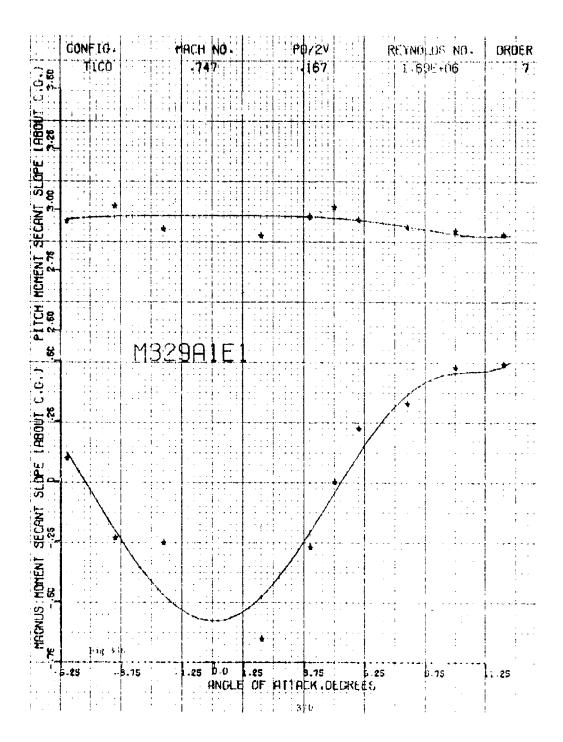
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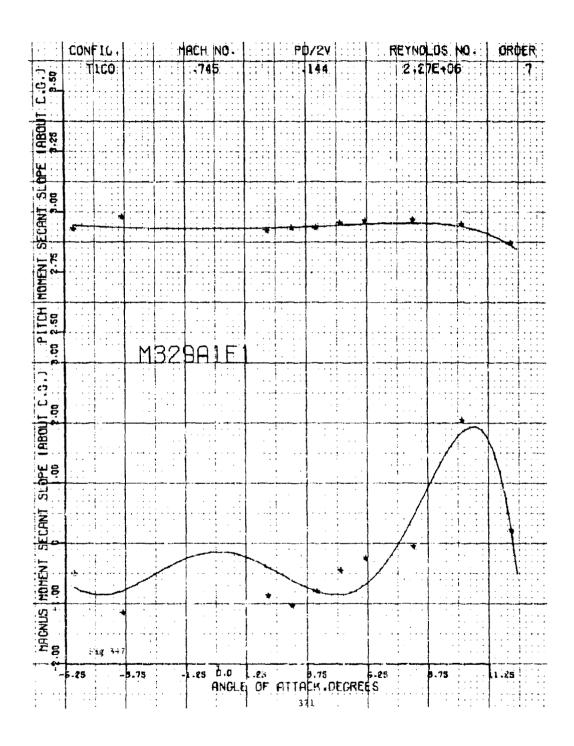
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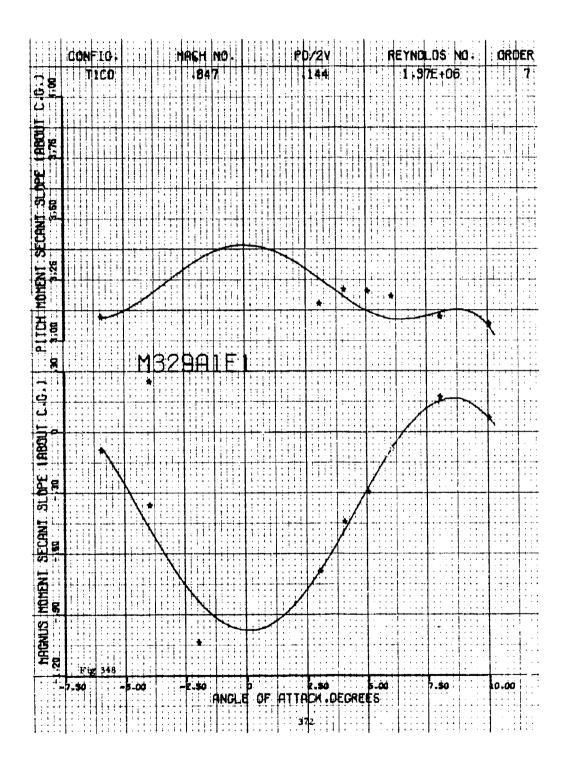


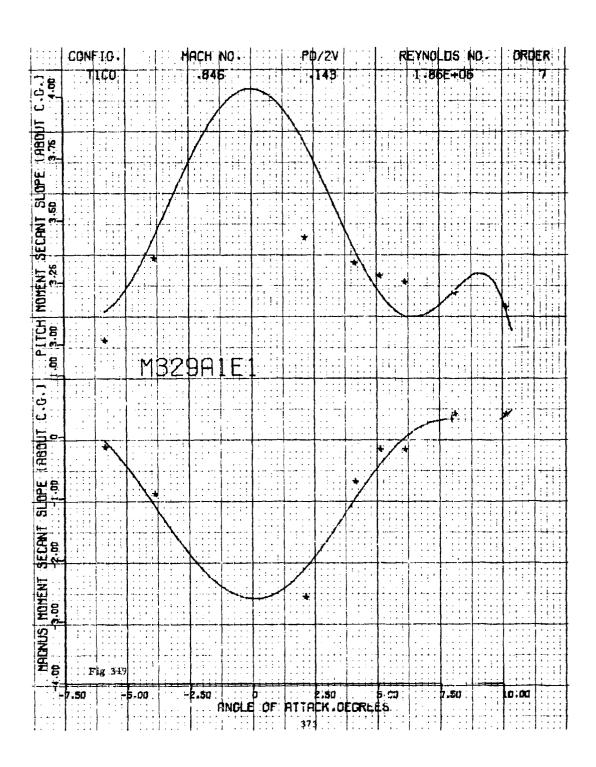


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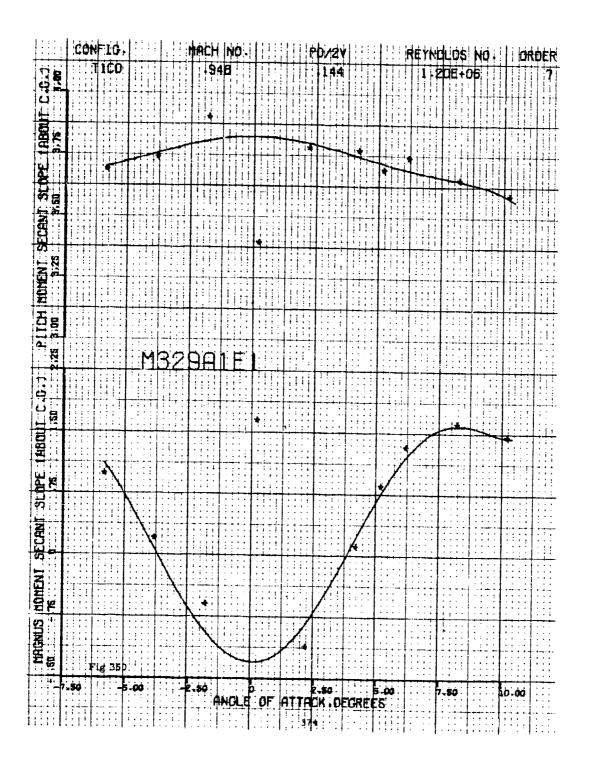


Fig 35

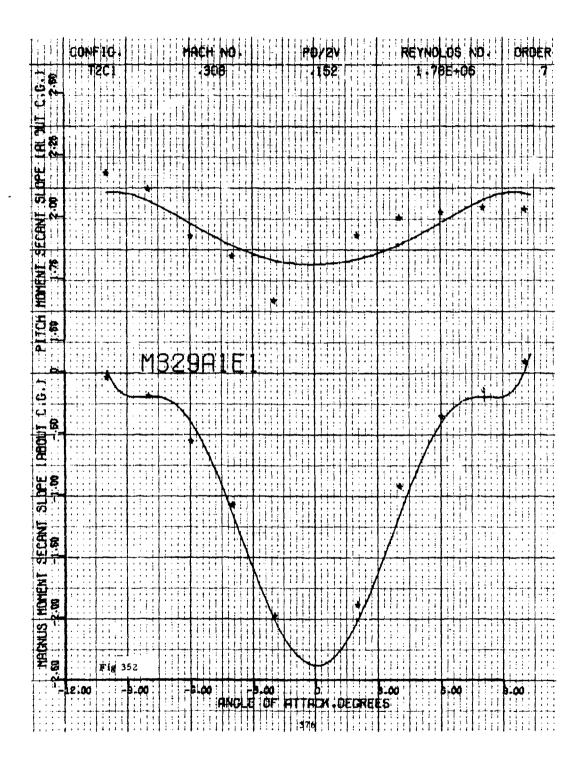
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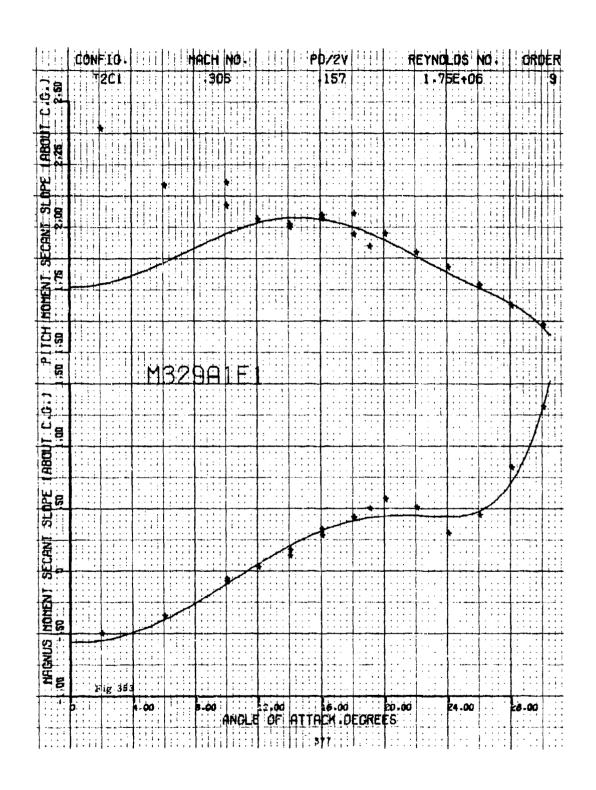
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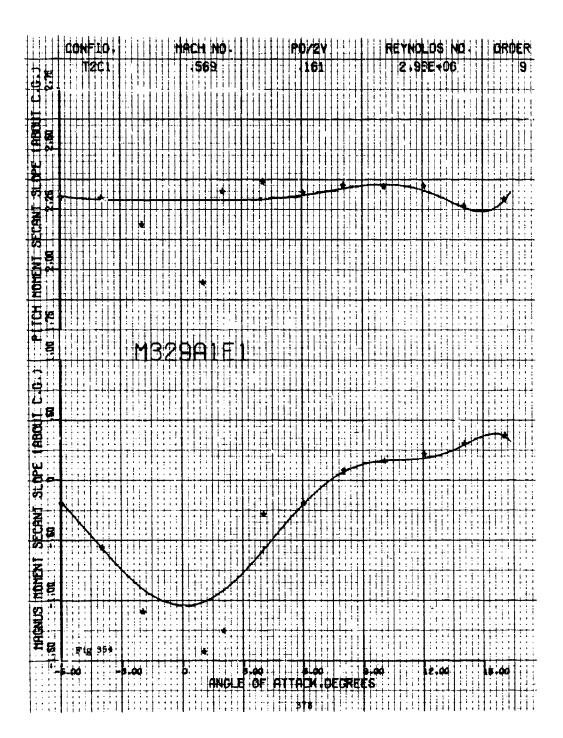
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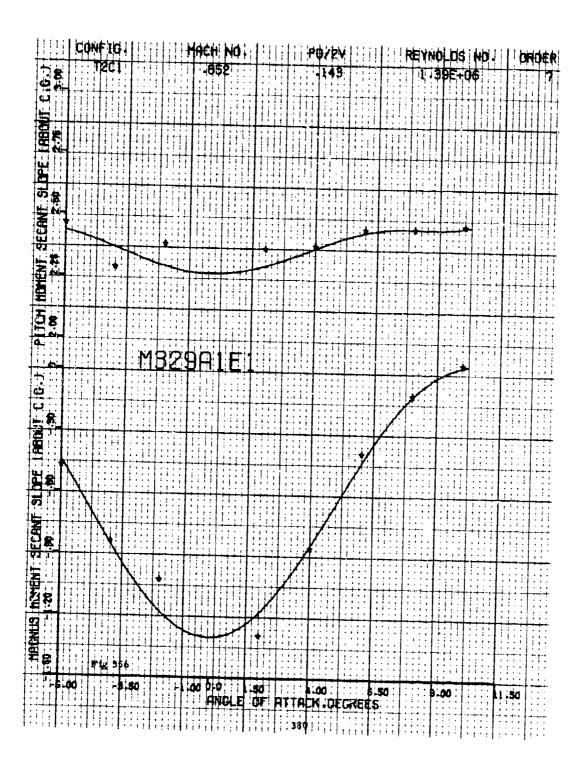


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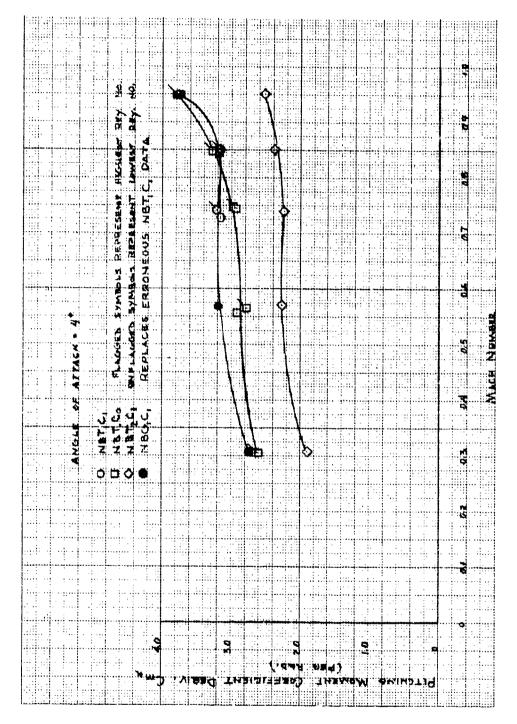
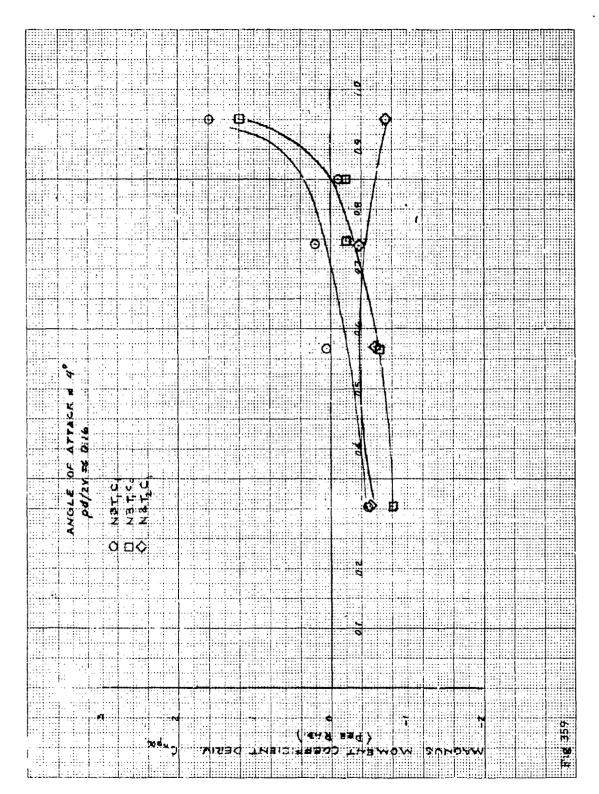
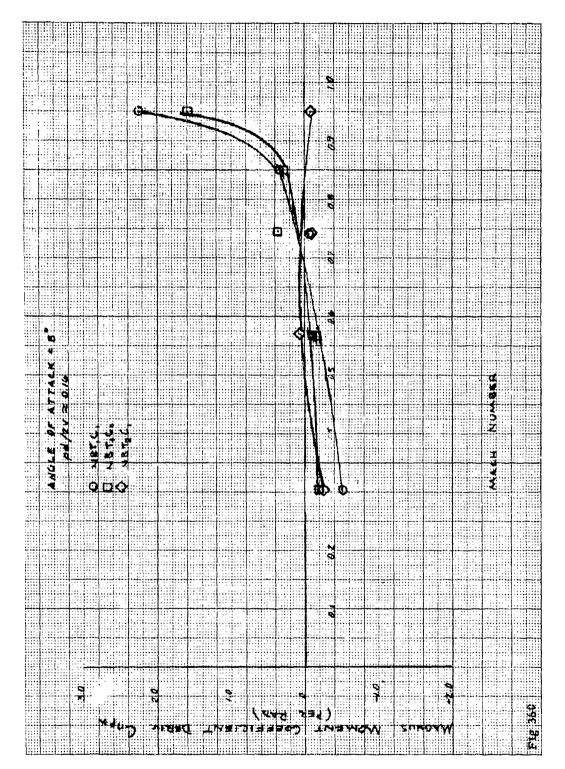


Fig 358 Pitching moment coefficient derivative vs Mach No. (NBT $_1$ C , NBT $_2$ C , NBT $_2$ C , NBG $_1$ C)

Figures 359 and 360

 $\begin{array}{c} \text{Magnus moment coefficient derivative vs Mach No.} \\ \text{(NBT}_1 {}^C_1, \text{ NBT}_1 {}^C_0, \text{ NBT}_2 {}^C_1) \end{array}$

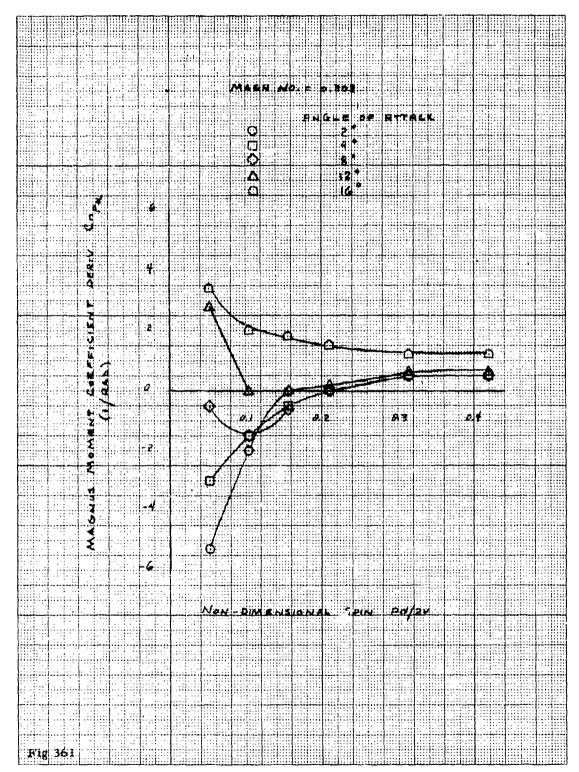


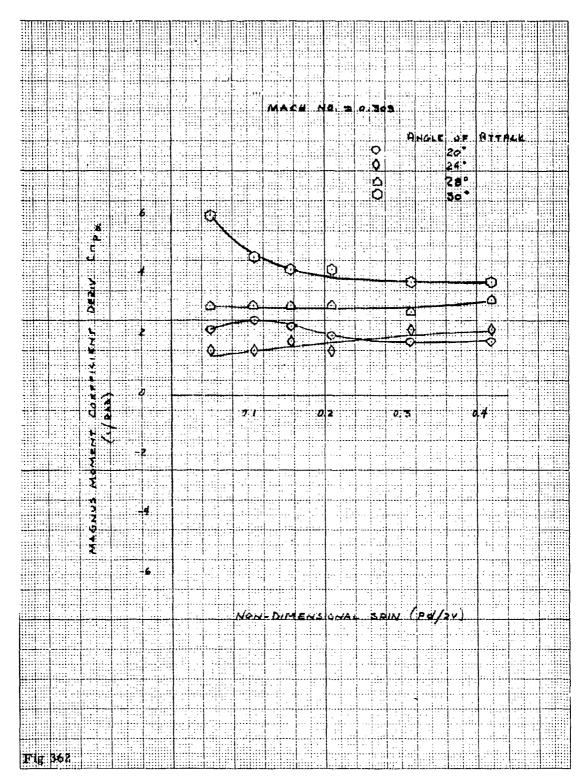


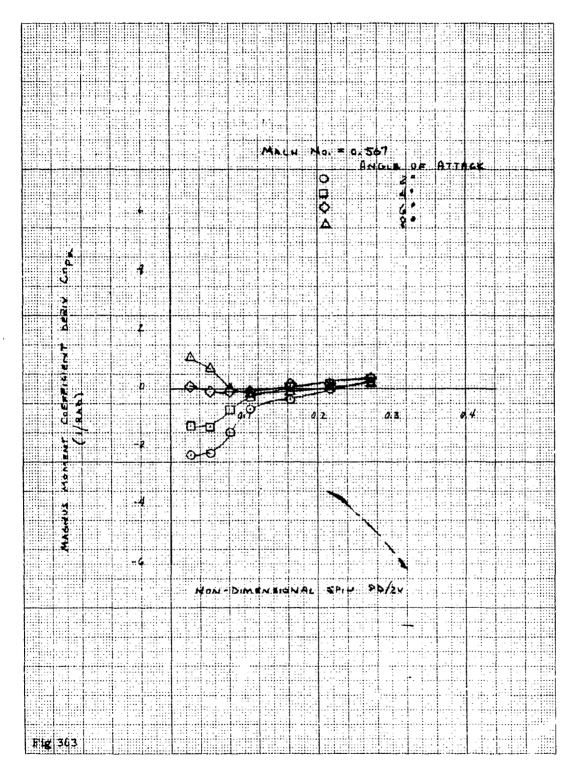
Figures 361 through 367

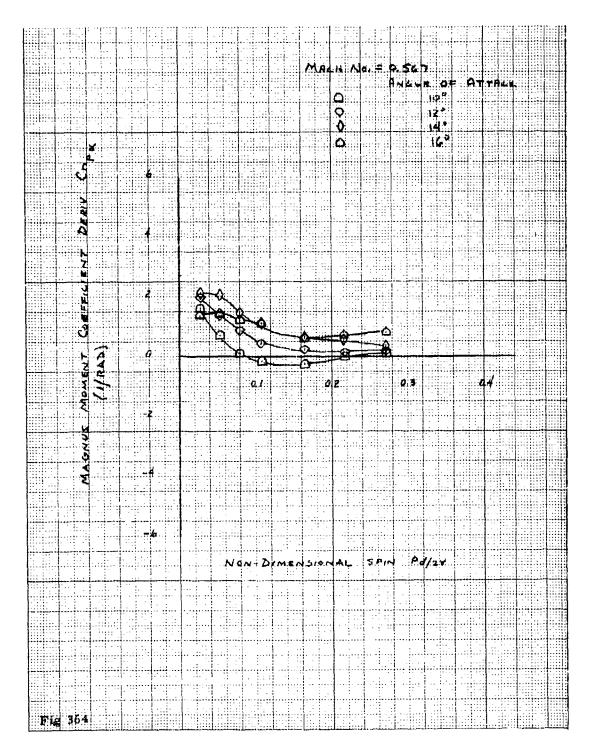
Magnus moment coefficient derivative vs pd/2V (NBT_1C_1)

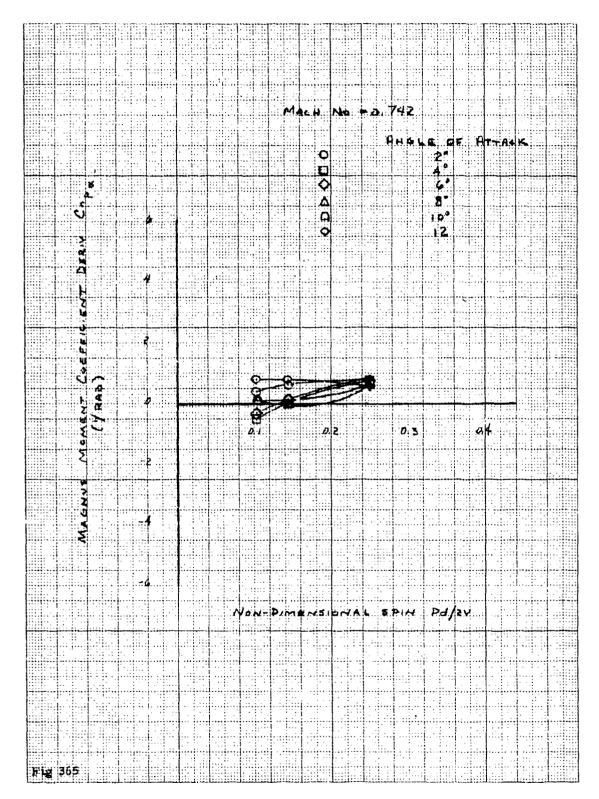
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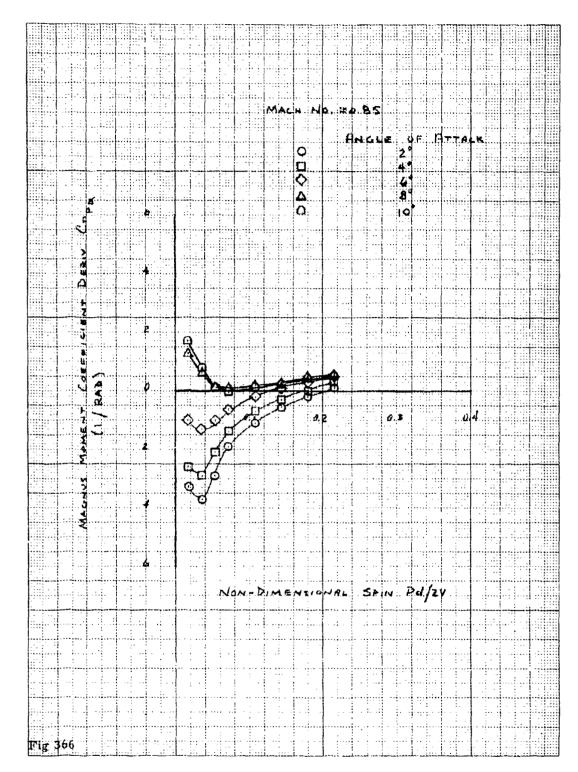


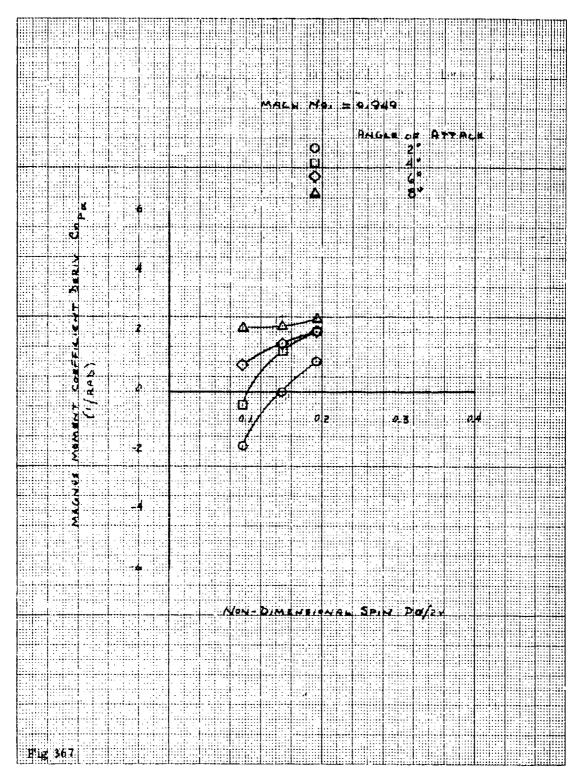






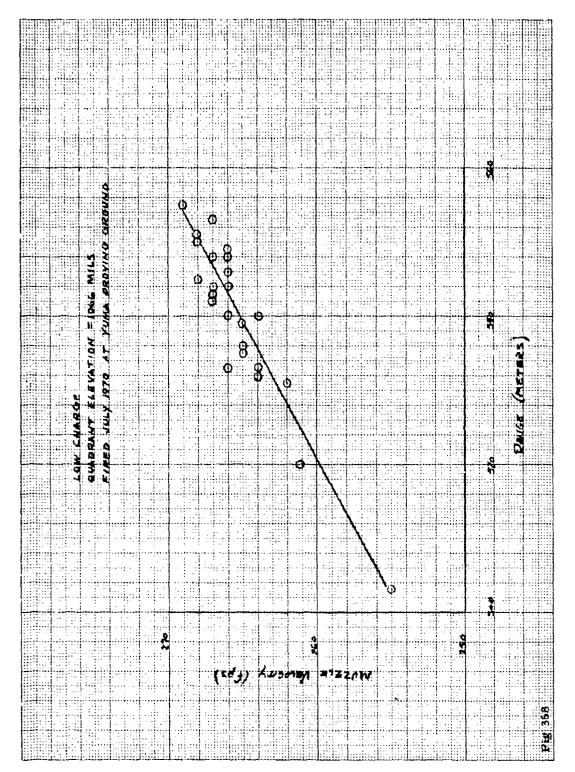


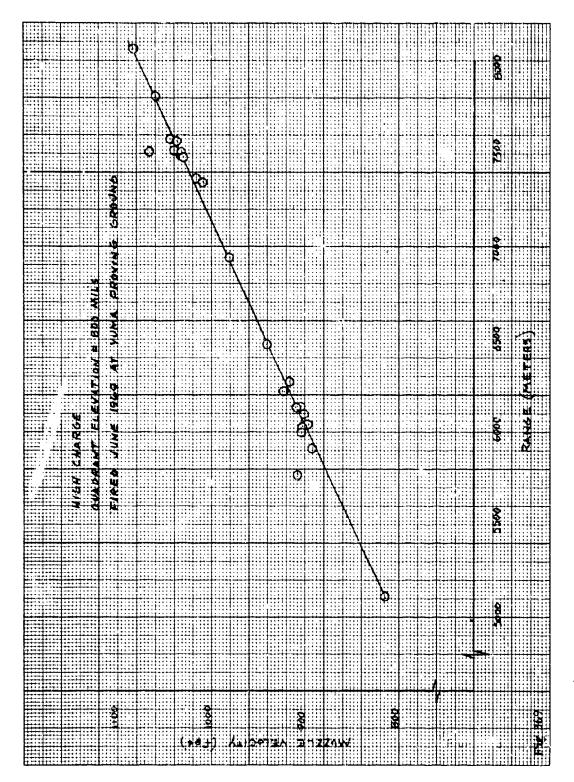




Figures 368 through 369

Muzzle velocity vs range for performance flight tests at Yuma Proving Ground



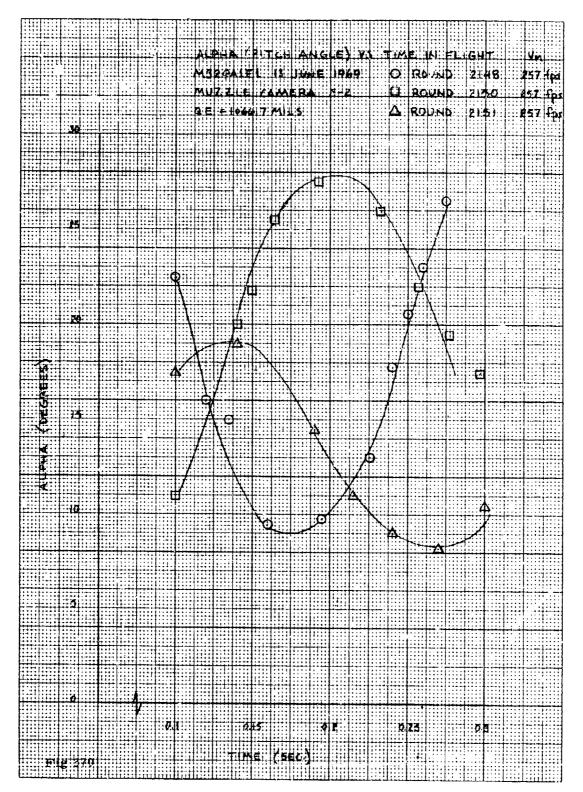


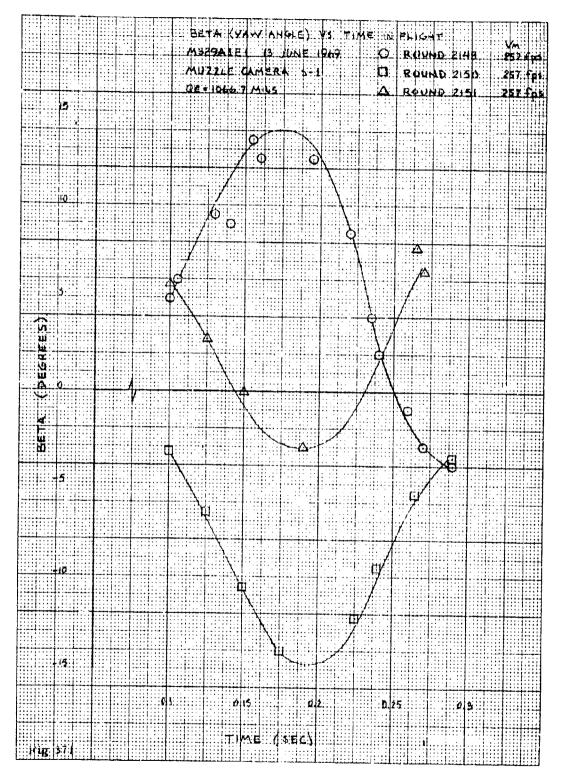
Figures 370 through 374

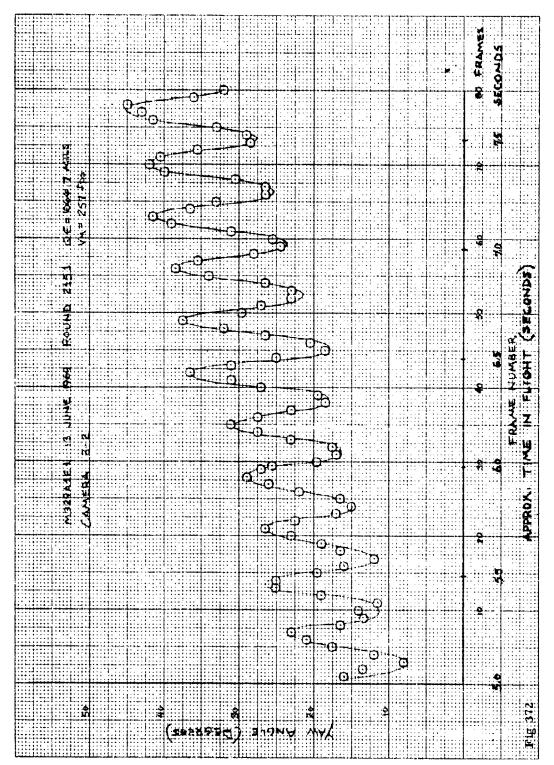
Yaw data translated from camera coverage shown in Figure 8

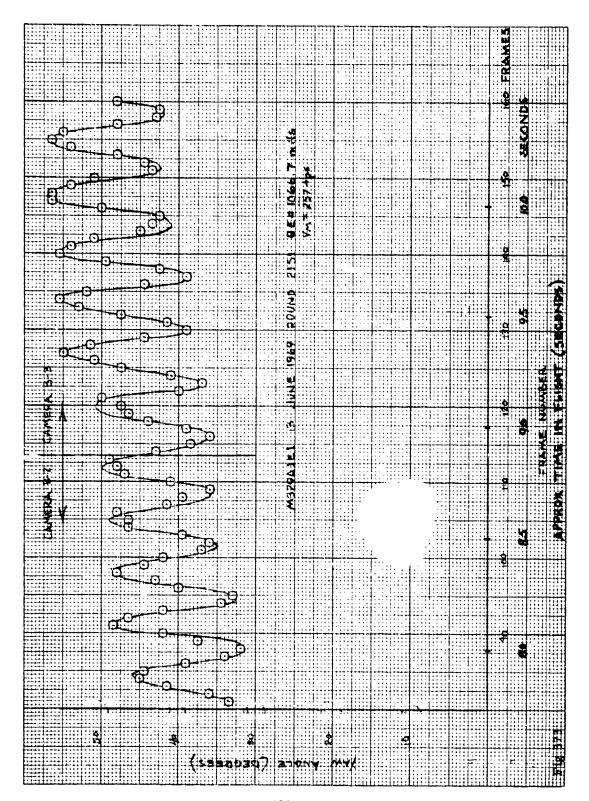
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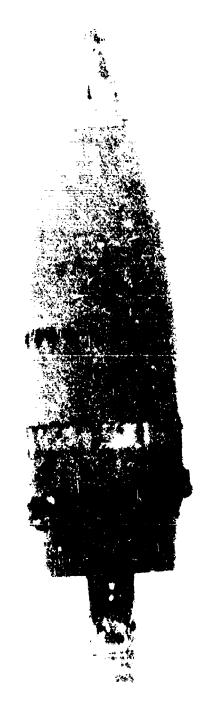


Fig 375 M329A1E1 projectile fired at low charge, with obturator still attached

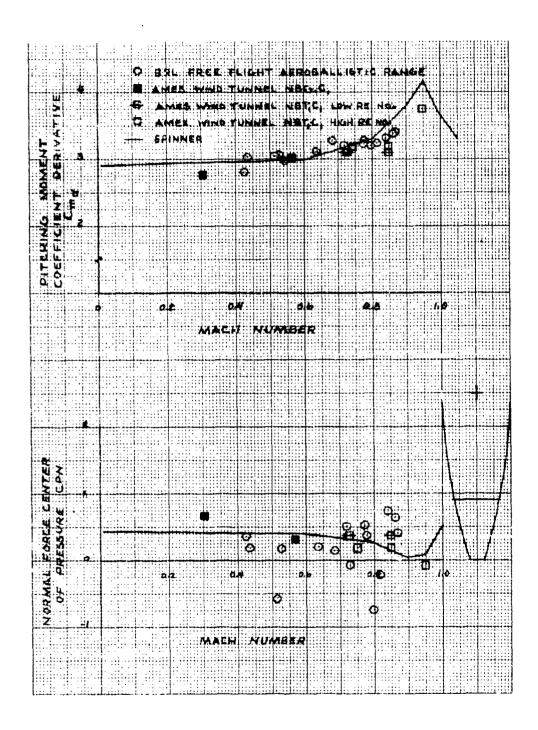


Fig 376 Pitching moment coefficient derivative and normal force center of pressure vs Mach No. (SPINNER and the BRL Transonic Range) $({\rm NBG_1C_1},\ {\rm NBT_1C_1})$

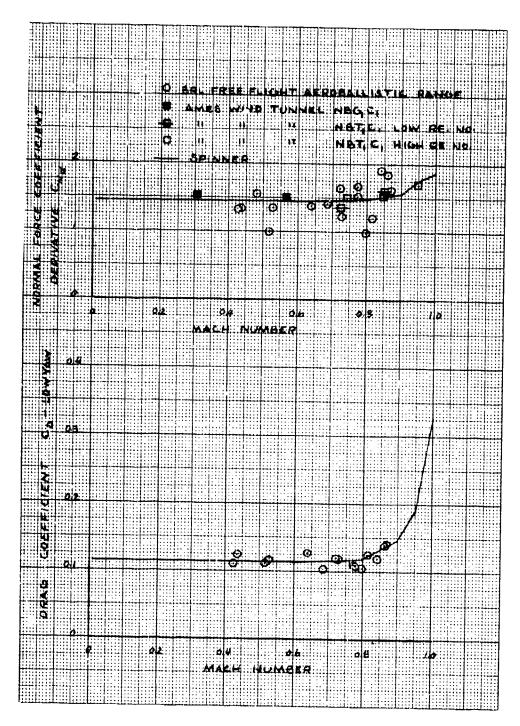
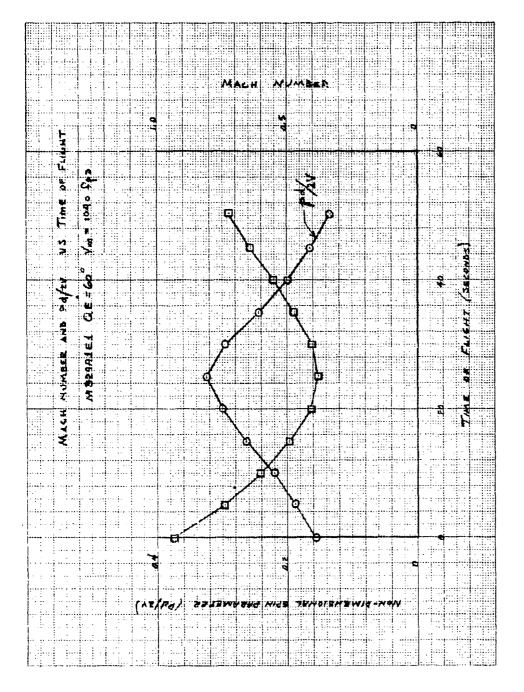
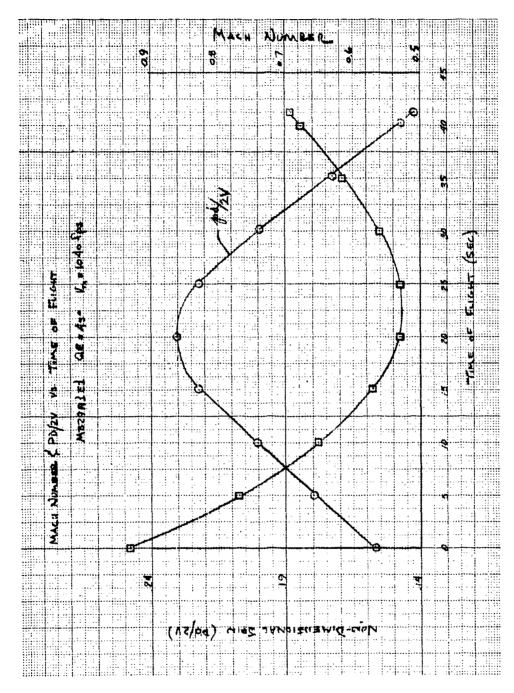


Fig 377 Normal force coefficient derivative and drag coefficient vs Mach No.
(SPINNER and the BRL Transonic Range)



Mach No. and pd/2V vs time of flight for M329AlE1 six-degree of freedom , $V_{muzzle} = 1040 fps$) trajectory computer simulations. (QE = 60°. Fig 378



Mach No. and pd/2V vs time of flight for M329AlE1 six-degree of freedom trajectory computer simulations. (QE = 45°, Vmuzzle = 1040 fps) Fig 379

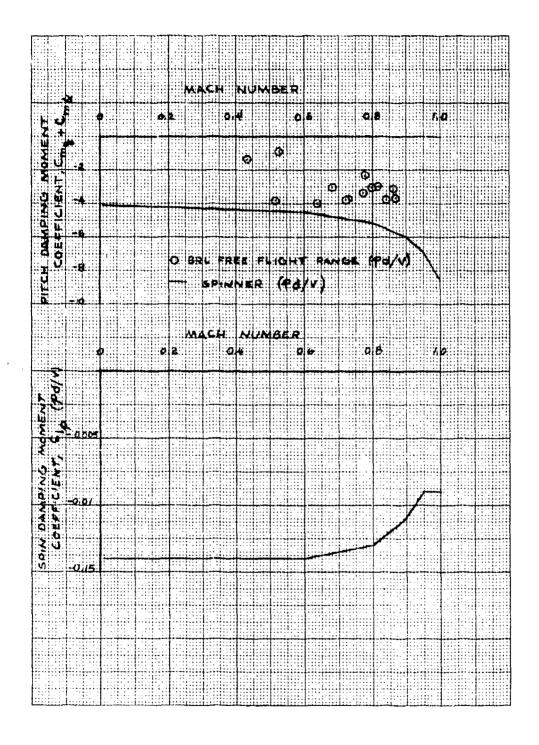


Fig 380 Pitch damping coefficient and spin damping coefficient vs Mach No.

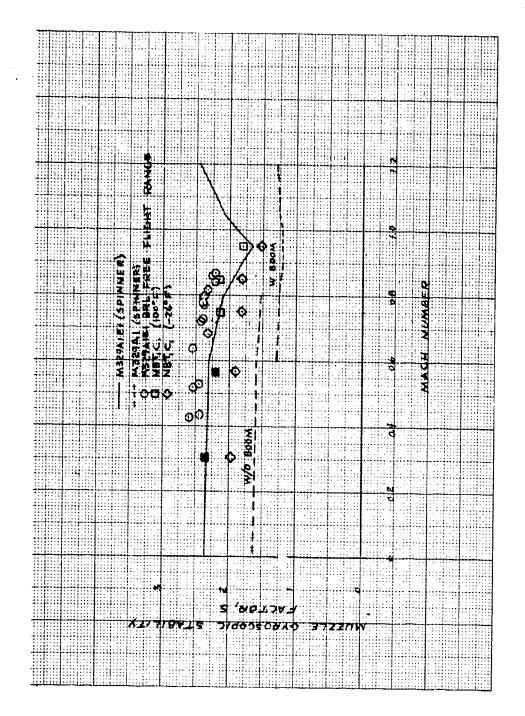
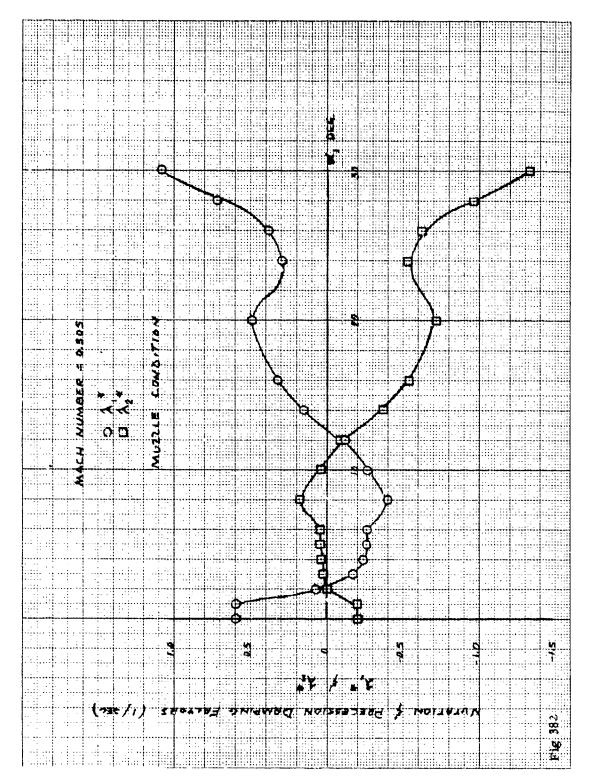


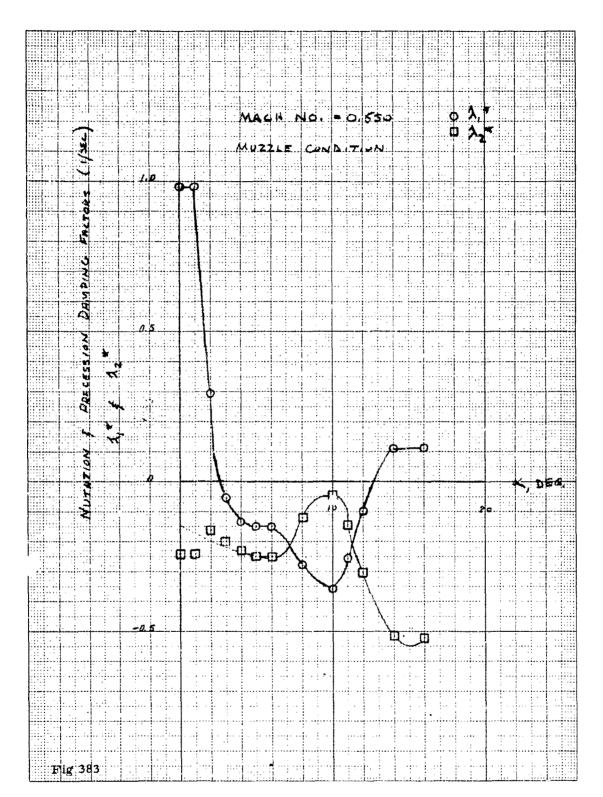
Fig 381 Muzzle gyroscopic stability factors vs Mach No.

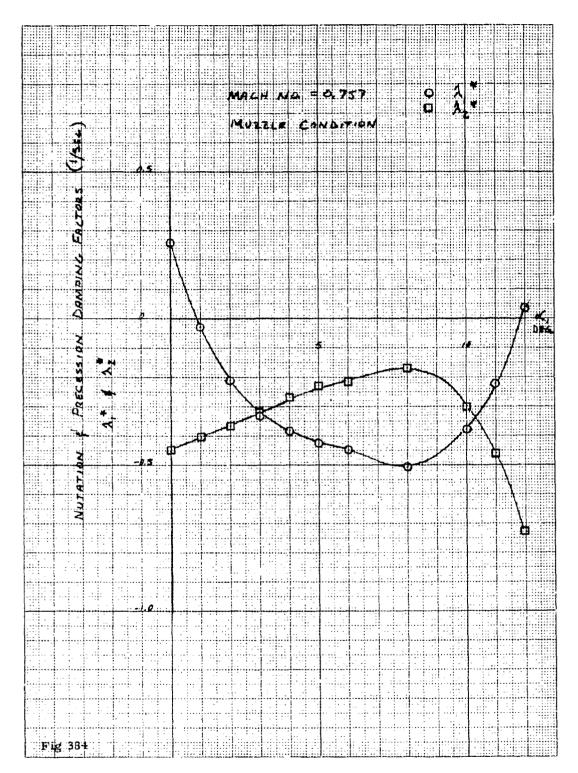
Figures 382 through 386

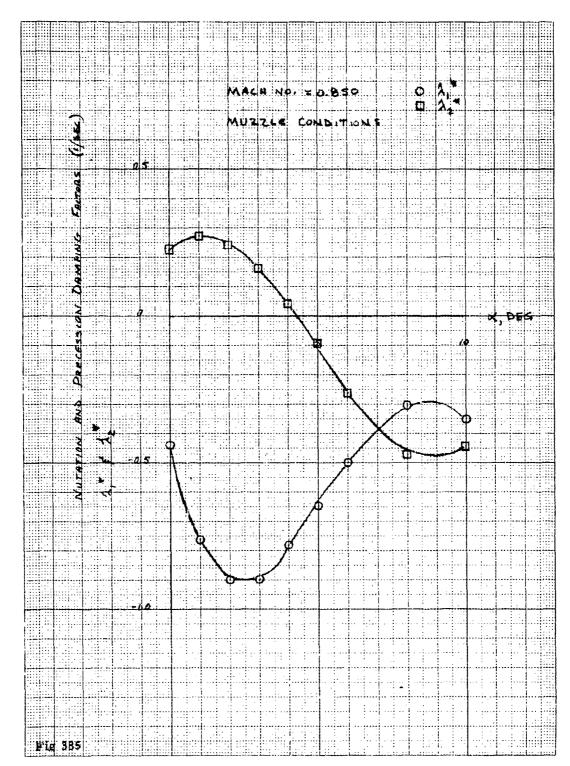
Damping factors vs angle of attack for configuration $\operatorname{NBT}_1\mathbf{C}_1$ at various Mach numbers

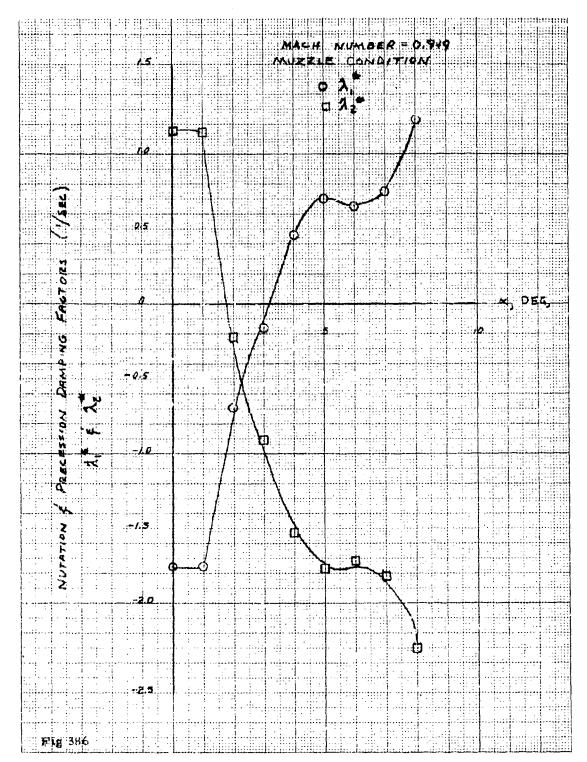
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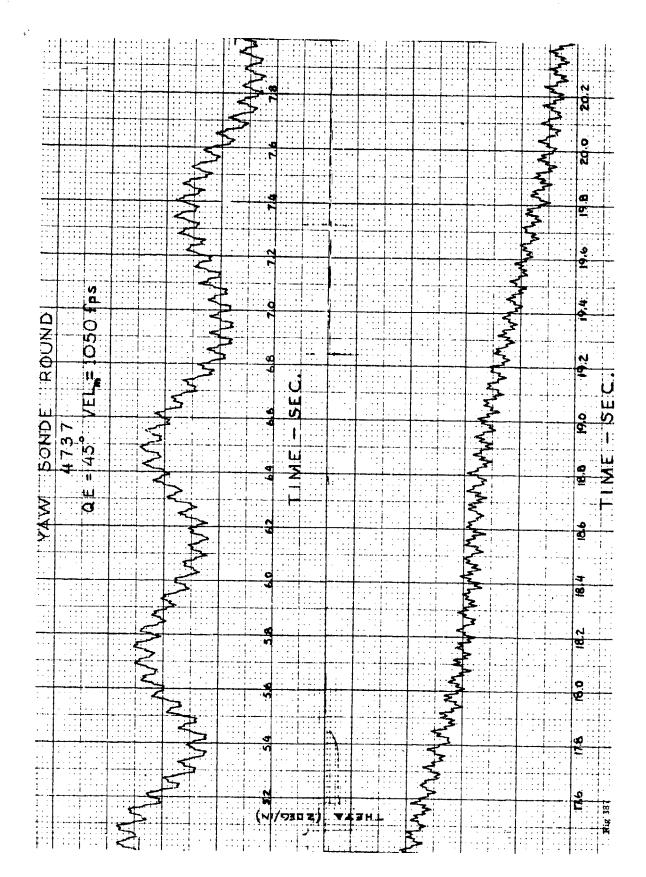


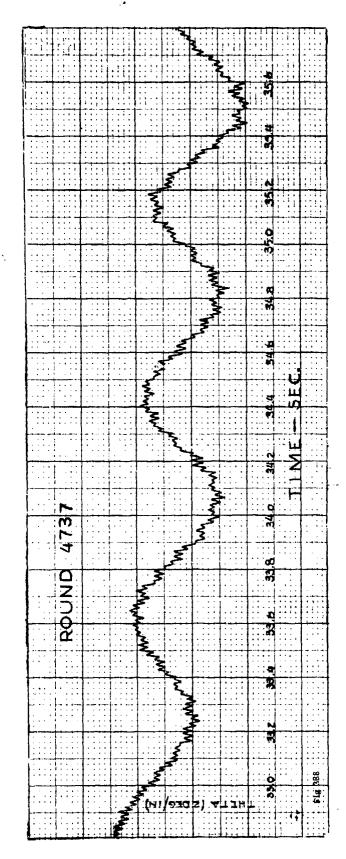


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Figures 387 and 388

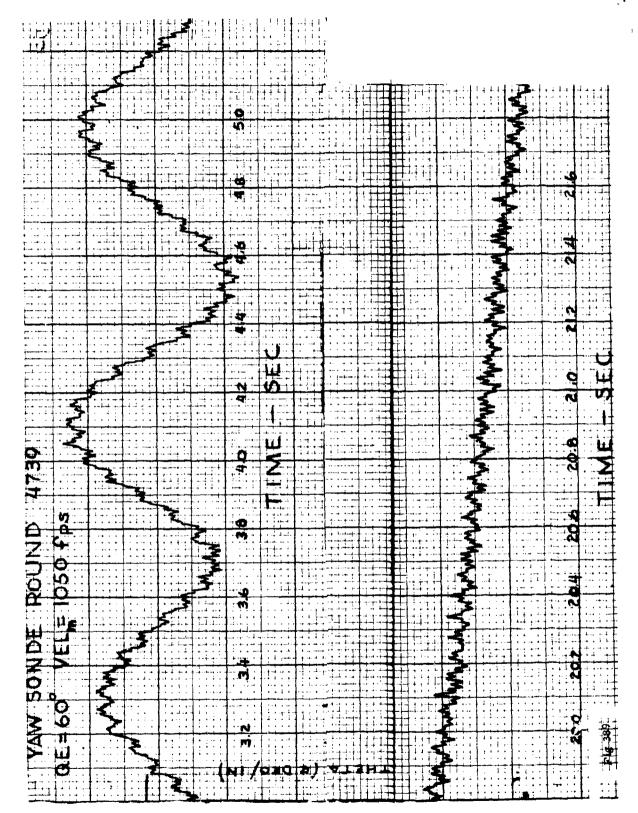
Solar aspect angle vs time of flight for M329A1E1 yaw sonde Round No. 4737

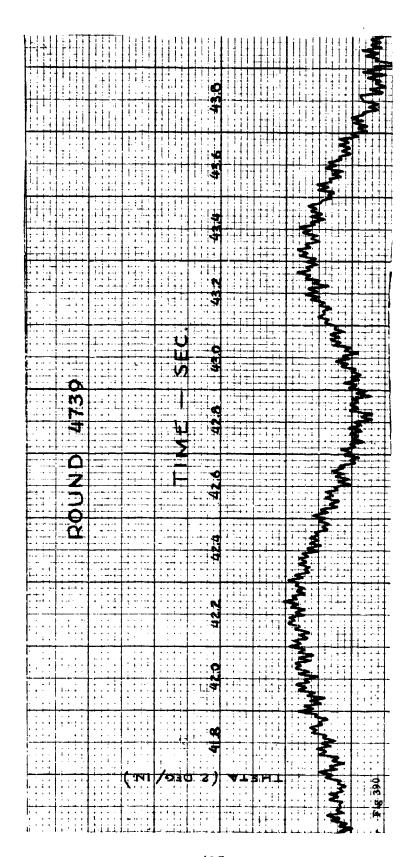




Figures 389 and 390

Solar aspectangle vs time of flight for M329A1E1 yaw sonde Round No. 4739





Figures 391 and 392

Solar aspect angle vs time of flight for M329A1E1 yaw sonde Round No. 4740

